
DESIGN REQUIREMENTS FOR A TENDON REHABILITATION ROBOT: RESULTS FROM A SURVEY OF ENGINEERS AND HEALTH PROFESSIONALS

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Abstract

Exoskeleton type finger rehabilitation robots are helpful in assisting the treatment of tendon injuries. A survey has been carried out with engineers and health professionals to further develop an existing finger exoskeleton prototype. The goal of the study is to better understand the relative importance of several design criteria through the analysis of survey results and to improve the finger exoskeleton accordingly. The survey questions with strong correlations are identified and the preferences of the two respondent groups are statistically compared. The results of the statistical analysis are interpreted and insights obtained are used to guide the design process. The answers to the qualitative questions are also discussed together with their design implications. Finally, Quality Function Deployment (QFD) has been employed for visualizing these functional requirements in relation to the customer requirements.

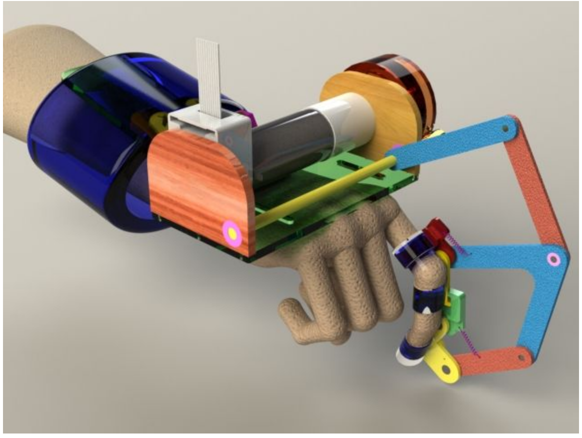


Figure 1: CAD DRAWING OF THE DEVELOPED REHABILITATION ROBOT (FINGER EXOSKELETON)

INTRODUCTION

Rehabilitation Robots

Physical therapy involves exercising and manipulating the body to improve joint and muscle function [1]. In health sciences, rehabilitation has traditionally been carried out through extensive time allocation by professional physiotherapists. Most of the time that a therapist spends with a patient is dedicated to a set of repetitive physical movements, either assisted or completely performed by the therapist [2]. The rising demand for the health services and the lagging supply of experienced therapists is a major impediment to the effective practice of rehabilitation treatment, especially in developed countries with aging populations.

Rehabilitation robots significantly relieve therapists from the burden of intense physical interaction with the patient. The robot also relieves from the stress of extreme attention that the therapist must continuously give to avoid any injuries. The assistance of a rehabilitation robot also allows doctors and therapists to observe the progress of the patient's healing process and focus on the selection of the right treatment methods.

Rehabilitation Exercises

According to the Merck Manual [1], there are three types of range of motion (ROM) exercises in physical therapy: 1) *Active* exercise is when a patient can exercise a muscle or joint without help, by her/himself. 2) *Active-assistive* exercise is when a patient can move her/his muscles with some help from the therapist or can move their joints with feeling of pain. 3) *Passive* exercise takes place when a patient can not actively perform the exercise, and does not exert any effort in doing so. Instead, the therapist moves the patient's limbs. The latter two ROM exercises are performed very gently to avoid any injury. In addition to these three types of exercises, *resistive* ROM exercise can be mentioned. This is when a patient actively performs the exercises, but has to overcome certain applied resistance applied by the therapist during the movement [3]. In part of the literature, resistive exercise is considered within the scope of active-assistive exercise.

Since these exercises are done for the purpose of rehabilitation, they also define the types of therapy. Thus, the terms *active therapy, active-assistive therapy, passive therapy* and *resistive therapy* refer to the application of the respective exercises by a therapist or a robot.

Tendon Injury

Hand tendons consist of *flexor tendons* and *extensor tendons.* Flexor tendons connect muscles of the forearm to the bones of the thumb and the fingers, and enable the flexion of the fingers. Extensor tendons connect the muscles of the forearm and hand to the bones in the fingers and the thumb, and are enable the extension (straightening) of the fingers. The most common and disturbing problem that patients experience after a tendon injury is finger stiffness, that is, the inability to either fully bend (*flexor tendon injury*) or straighten the finger (*extensor tendon injury*). Avoiding finger stiffness requires complete recovery of tendon excursion so that the full ROM of the finger is re-gained.

Tendon Therapy

In many references, efficacy of early mobilization of the finger, starting within a few days of repair, is advocated. In particular, early mobilization techniques are claimed not only to inhibit adhesion formation but also to promote intrinsic healing, producing a stronger repair site compared to immobilization of the injured tendon [4]. The major challenge during implementation of early mobilization techniques is to ensure that an appropriate amount of stress is induced to overcome internal resistance to initiate tendon gliding but not to cause gap formation or breaking of the suture.

There exists two commonly used early mobilization techniques for rehabilitation of hand function due to a tendon injury: The *modified Duran technique* and the *Kleinert technique.* In the modified Duran technique, a therapist enforces coordinated motions to the injured finger within closely controlled joint limits while the patient stays passive throughout the therapy [5]. The Kleinert technique utilizes a dynamic splint that attaches the proximal phalanx of the finger to the wrist with a rubber-band and constrains the wrist movements. For flexor (extensor) tendon injuries, the rubber band applies forces to aid flexion (extension) of the finger. The resistive therapy of the Kleinert technique combines active and passive movements of the finger such that the patient stay passive while flexing (extending) the injured finger, while the patient is active during extension (flexion) of the finger [6].

LITERATURE AND SCOPE OF THE STUDY

Literature

The growing field of rehabilitation robots has the potential to be an integral part of physical therapy, and therefore the treatment of many illnesses. However, there exists significant uncertainty on how much the developed rehabilitation robots really meet the requirements of the treatment process, and the requirements of the parties involved in the process [7]. These parties are the patients who are subject to the treatment and the health professionals (doctors and therapists) who apply the treatment.

The earliest studies with user surveys on rehabilitation robots are by Dijkers et al. [8] and Stanger et al. [9]. Our paper follows a data analysis approach similar to that of [10], distinguishing between quantitative and qualitative questions. In contrast to the mentioned studies, our paper focuses especially on the mechanical design of the robot, including detailed querying of its mechanisms, since the second group of respondents consists of engineers.

Research Question

In this paper, a structured survey—with both quantitative and qualitative questions—is applied to engineers and health professionals, for answering a design-oriented research question: *"How can a prototype tendon rehabilitation robot be improved, based on Voice of Customer (VOC)?"* Health professionals are the real customers of the developed product, since they are the ones who will decide on whether or not to use it as a part of their professional practice. Voice of engineers is important, since they are the ones involved in the design and development. Engineers are also customers in a sense, since they are also potential patients that may one day receive therapy through the rehabilitation robots. To the best of our knowledge, no paper until now has reported the survey of these two groups within the same study, regarding a rehabilitation robot.

The ultimate goal of the presented work is to shape the developed prototype robot based on user feedback. The findings in the study can also be applicable to the design of similar robots in the physical therapy domain.

Motivation

The costs of providing high quality health care are steadily rising throughout the world. For example, the cost of medical services alone in US was $961 billion in 2000. In 2007, it was estimated to be $1.584 trillion [11], increasing by 65% compared to 2000.

A 2009 survey by Christopher Reeve Paralysis Foundation [12] reports that 1,275,000 people in the United States are living with spinal cord injury, requiring physical therapy on hands, limbs and/or other parts of the body. This is more than five times the number of Americans previously estimated in 2008. Thus the demand for physical therapy is also increasing, together with the increased demand for health services overall.

Approximately $600 million of the US health expenditures in 2007 consisted of the aggregate pay to therapists. Strikingly, while the health expenditures are increasing, the number of therapists in the US has stayed the same from 2006 to 2007, and the yearly wage of a therapist has increased by nearly $8000 [13].

The human hand is vital for performing most of the activities of daily living tasks. Hand injuries are common results of accidents. More than one million people all over the world receive treatment in emergency departments annually due to acute hand and finger injuries. Tendon injures are among the most frequent problems among the hand-related injuries [14]. The loss of hand function is a major source of disability which prevents patients from performing their daily activities. This health problem also limits the patients' employment opportunities.

Scope of the Study

Patients that experience tendon injuries are traditionally rehabilitated by the help of physical therapists. But this method is costly for the patient and time consuming for therapists as they have to personally assist every patient. A well-designed exoskeleton can bring efficiency to the therapy process, and a prototype rehabilitation robot has been developed at Sabancı University [15] for this purpose.

While designing a rehabilitation robot, safety is the most crucial necessity to be considered. Dosage and speed of the exercises should be adjusted well to provide this. Also, ergonomics of the robot should be suitable to patients requirements. Apart from safety, user friendliness and comfort are the two other important factors that a rehabilitation robot has to acquire.

A usability study with four non-patient subjects has been carried out in an earlier study [15] , and the effectiveness of the robot has been demonstrated. The goal of the study presented here is to improve the robot through feedbacks of engineers and health professionals (doctors and therapists).

THE DEVELOPED REHABILITATION ROBOT

Rehabilitation Devices for Tendon Injury

In the literature, various finger/hand exoskeleton devices have been developed for rehabilitation of finger/hand function. However, most of these devices target the treatment of stroke patients.

However, the design of finger exoskeleton and administration of tendon therapy need be handled separately, since the challenges involved in robotic assisted tendon therapy exercises are significantly different than other robot-assisted therapies.

An under-actuated finger rehabilitation system, specifically designed for the tendon repair therapy exercises, has been readily developed at Sabancı University (Figures 1 and 2), and usability tests have been performed [15]. The system can provide quantitative measurements of finger movements, interaction forces, and muscle activities, assist the finger motion within its full range in a natural and coordinated manner, and keep the tendon tension within acceptable limits to avoid gap formation or rupture of the suture. Several other hand and finger exoskeletons have been developed by different research groups around the world, and these are listed in Appendix A of a supplementary document [16].

Design of the Finger Exoskeleton

The design of the finger rehabilitation robot is presented in Figure 1, and its support for flexion movements is given in 2. The design and the mechanics of the robot will now be described.

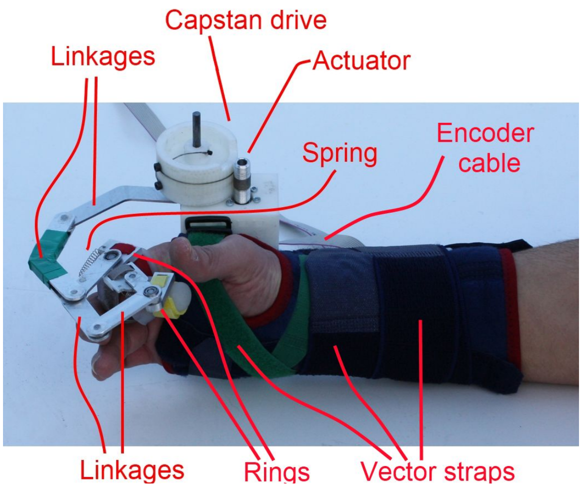


Figure 2: FLEXION POSITION DURING THE USAGE OF THE ROBOT

A finger exoskeleton that is appropriate for treatment of tendon injuries is required to cover the whole natural ROM of the flexion/extension motion of each joint of the finger. Hence, the mechanism must attain at least three degrees of freedom (DoF). Ergonomics also necessitate that the kinematics of the exoskeleton supports the natural finger motions without any interference and ensures that the rotation axes of the human finger is aligned with the joint axes of the exoskeleton. A parallel kinetic mechanism is adapted for the finger exoskeleton, for which the kinematics of the human finger is an integral part of the device kinematics. The device is operational only when worn by a human operator. The linkage-based kinematic structure of the parallel mechanism is advantageous over cable-driven transmission mechanisms, since the linkages allow for direct and efficient transfer of forces form the grounded actuators to each phalanx of the finger.

Having three DoF, up to three independent actuators can be utilized to control the mechanism. However, for physical therapy exercises following tendon injuries, independent motion of each phalanx of the finger is hardly necessary as long as a wide range of coordinated finger motions can be supported and the whole RoM of the finger is covered. Hence, an under-actuated mechanism is selected for the kinematic structure of the finger exoskeleton. Compliant springs are used for the mechanism to ensure a coordinated motion of the phalanxes.

The robot's mechanism is capable of reproducing many of the natural finger trajectories and the actuator forces are distributed over all phalanxes. The spring pre-load at each joints can be customized to accommodate patients with different finger tone levels.

The weight of the finger exoskeleton is kept low by using 6061 aluminum to fabricate the links and hard plastic to manufacture the grounded bracket and the capstan transmission. The overall device weighs 185g without the actuator. The weight of the device is distributed over the wrist and forearm using an adjustable splint. Weight of the device can further be distributed over the body by relocating the actuator away from the wrist. Mechanism is attached to the finger using disposable soft silicon rings trapped by tight Vectro straps. The finger exoskeleton is actuated by a direct drive DC motor driven capstan transmission equipped with an optical encoder.

Currently, the proposed finger rehabilitation system supports all four modes of tendon repair therapy, namely, active, active-assisted, passive-assisted, and resistive (*active-constrained*) modes.

In addition to offering robot assisted operation modes for tendon therapies, the exoskeleton can provide quantitative measures of recovery that can help guide the physical therapy program. Usability studies have been conducted and efficacy of exoskeleton driven exercises to reduce muscle requitement levels has been demonstrated [15].

METHODOLOGY

A survey has been designed and conducted on two groups, engineers and health professionals (doctors and physiotherapists) to improve the developed robot.

The survey consists of three categories of questions: *Common Questions, Questions for Engineers,* and *Questions for Health Professionals*. Common questions were posed to both groups, and the questions in the other two categories were posed only to the relevant groups. The survey questions are given in an accompanying supplementary document [16].

There are five questions in the common questions category, and these query the relevance of robots and the importance of several design requirements. The first page of the survey includes the photograph that shows the flexion position 2 (without the labels), as well as another one that shows the extension position. The questions in this category were used in the Quality Function Deployment (QFD). The WHATs in the QFD chart (House of Quality - HOQ) have been mainly selected from the design requirements in this category.

Before the second category of questions, engineers were presented with a summary of the the robots technical capabilities and characteristics. The second category includes 10 questions, with each of them querying the engineers' opinions on engineering design questions.

The third category of questions, posed to health professionals, were preceded by an explanation of the robot, written in a style that would appeal to health professionals. The third category includes 20 questions, most of them being open-ended.

Before conducting, the survey was refined three times. At each iteration, brainstorming sessions and discussions were held within the project group. The final version of the survey was sent to a total of 50 possible participants, consisting of engineers, orthopedists, and physical therapists. The survey was eventually filled by 17 engineers and 18 health professionals, all residing in the Turkish cities of Istanbul, Konya, and Antalya. The three cities are scattered in the Western half of Turkey, and have distinct demographic characteristics, increasing our subjective confidence in the representativeness of the sample.

ANALYSIS AND RESULTS

The results of the survey are analyzed in this section. The quantitative questions are distinguished with a superscript star *.

Many of the questions that were qualitative in the survey have been transformed to quantitative questions, to enable more extensive statistical analysis. For example, the answers in a Yes/No question were represented with the values of 1 and 0. For the questions which included "No opinion" as an answer, the "No opinion" answer was considered as missing data.

Exploratory Data Analysis

Table 1 presents the summary statistics for the quantitative common questions. A03g* (safety) has the highest normalized score and A04* (appearance) has the lowest normalized score. Table 2 presents the summary statistics for the quantitative customized questions. Here, B06* (fixing of the robot), C02a* (freedom of movement), C04* (ergonomics), and C14* (need for customizing exercises for patients) have the highest normalized scores. Exploratory graphs for all the quantitative questions are given in Appendix B of the supplementary document [16].

Table 1: SUMMARY STATISTICS FOR QUESTIONS WITH QUANTITATIVE ANSWERS –QUESTIONS FOR BOTH GROUPS

QuestionID	N	Blanks	Max	Mean	Stdev
A01*	35	0	4	3.26	0.95
A02*	35	0	4	3.29	0.79
A03a*	35	0	5	4.37	0.97
A03b*	35	0	5	3.94	0.97
A03c*	35	0	5	4.37	0.91
A03d*	35	0	5	4.17	0.92
A03e*	35	0	5	3.74	1.22
A03f*	35	0	5	4.31	0.80
A03g*	35	0	5	4.57	0.81
A03h*	35	0	5	4.14	0.97
A03i*	35	0	5	4.37	1.03
A04*	35	0	4	2.80	0.72
A05*	35	0	4	3.17	0.86

Table 2: SUMMARY STATISTICS FOR QUESTIONS WITH QUANTITATIVE ANSWERS – GROUP-SPECIFIC QUESTIONS

QuestionID	N	Blanks	Max	Mean	Stdev
B01*	35	18	3	2.71	0.59
B02*	35	25	3	2.80	0.63
B03*	35	18	3	2.24	0.83
B05*	35	22	3	2.69	0.63
B06*	35	18	**3**	**2.82**	0.39
B07*	35	18	1	0.29	0.47
C01*	35	17	3	1.67	0.91
C02a*	35	19	**5**	**4.69**	0.48
C02b*	35	20	5	3.53	0.92
C02c*	35	20	180	162.00	28.46
C04*	35	17	**3**	**2.83**	0.51
C08*	35	17	3	2.28	0.75
C14*	35	20	**1**	**0.93**	0.26
C15*	35	19	1	0.19	0.40
C20*	35	19	3	2.25	1.00

Perspectives of the Engineers

In the second part of the survey, opinions of 17 engineers were investigated on design-related issues. The questions involved the rehabilitation robots capabilities, how it works on tendon injuries, and its technical characteristics. Prior to the questions, a detailed explanation of the robot's design and operational mechanisms were presented to the responding engineers. The Kleirnet and Duran techniques, standard treatment methods practiced by therapists, were also described.

The questions asked solely to engineers, their answers, and the design implications are discussed below. The questions and the bar charts for the answers are given in Appendices B and C of the supplementary document [16]. Information regarding the mechanics of the design characteristics are also given in this document.

The answers to *quantitative* questions are discussed below:

B01*: Under-actuated Linkage Design

This question is related about the under-actuated linkage design of the robot. 13 of the 17 responding engineers agree on this design. Only one engineer does not agree, and three engineers are unsure. This design enables treatment methods to be customized for different patients. Under-actuated design does not allow as many controlled DoF as a fully-actuated design, since it does not allow for the concurrent movement of all phalanxes. Still, it is a better design due to advantages on cost, weight, safety and due to conforming with the normal anatomic movements of the fingers. Also, considering the patients psychology, light weight and comfort conditions are better in the under-actuated design.

B02*: Direct Drive & Capstan

This question asks whether using direct drive actuator and capstan transmission (as currently implemented) is appropriate. Among the 10 engineers with an opinion, all but one find this design appropriate. Direct drive actuator helps increase safety of the device upon unexpected failures by allowing patients move the robot with low resistance when the robot is assembled on the patients hand. Furthermore, capstan transmission decreases friction and eliminates backlash, allowing for smooth force control of the device.

B03*: Linkage-based Design

This question asks whether the current linkage-based design is more suitable than the alternative cable-based designs. 12 engineers find this design appropriate or somewhat appropriate. Linkage-based design permits transmission of forces directly to the phalanx of fingers. Moreover, such a design is more robust, easy to calibrate, and can work under the action of larger loads.

B05*: Linkage Thickness

This question asks whether the current thickness of the linkages (2mm) is appropriate. Using a light material is very important for patients comfort. Also a thin design allows two devices be used on two consequential fingers, without the links interfering with each other. Among the 13 engineers with an opinion, 10 find the thickness appropriate. 2mm is the right thickness because finding ball bearings smaller than this is infeasible with respect to cost. Moreover, below 2mm, deformations of the links can be experienced under unexpected large large . Thickness of more than 2mm decreases the free distances between the fingers and increases the weight. As a result, 2mm is an appropriate thickness.

B06*: Positioning of the Robot

This question asks whether the robots positioning on the wrist through hand is appropriate. To fasten the robot, a wrist brace has been used. the wrist brace has a supportive piece that keeps the hand perpendicular to the ground. Since the finger is out of plane with the ground, the patient is relieved from the burden of working against gravity. That is, s/he does not have to use her/his tendons to work against the weight of his finger and the effective weight of the device. All the 17 engineers agree that this positioning is appropriate or somewhat appropriate.

B07*: Enabling the Movement of the Wrist

This question asks whether a second actuator should be incorporated into the current design, to enable the movement of the wrist. 12 of the 17 engineers do not approve this change. The reasoning is that if an actuator is placed, then irrelevant muscles could also move causing extra stress to the injured tendon. Adding a second actuator would also increase the robots weight, cost and could negatively affect its aesthetics as well. Still, 5 of the 17 engineers believe that the wrist brace of the robot can be designed as two pieces, allowing adjustment of the wrist angle. A second actuator could regulate the angle between these two pieces.

Anatomically, wrist angle is an important parameter affecting the tension on the finger tendon. Thus there is strong motivation to enable different wrist angles in the robot. Accordingly, the renewed design of the robot has a manually adjustable-angle wrist fixture.

The answers of engineers to *qualitative* questions are presented in Appendix C of the supplementary document [16]. B04, B08, B10 are open ended questions, whereas B09 is a multiple-choice question. The answers to these questions are discussed below.

B04: Connecting the Last Phalanx

This question asks for opinion about a design decision regarding the robot. In the developed robot, every phalanx of a finger are placed in specially designed rings and connected via Vectro straps to the rings **??**. However, there is a problem regarding the last phalanx of the ring. The finger leaps out of the ring hole during flexion movement. There have been numerous suggestions, such as connecting to the rings by pasting the nail to the ring or holding the node tight with straps.

Actually, the problem was later identified as the improper force transmission of the device to the last link. In particular, the linkages applied too large of a horizontal force concurrently with the desired vertical force. The undesirable horizontal component caused the ring to slip out of the finger.

Following the survey, the finger exoskeleton was redesigned/redimensioned to address of this problem, by reducing the horizontal force transmitted to the distal phalanx.

B08: Material Selection

This question asks for the material to be used. Aluminum is the clear winner, with 12 of the 17 engineers selecting it. Aluminum has the advantage of having the best cost-performance combination in the market for such robots. 6061 aluminum is especially popular in real world applications. Some engineers suggested hard plastic or carbon fiber. Plastic parts need to be much thicker to support the same load as the aluminum, while manufacturing carbon fiber parts is costly.

B09: Fixing the Wrist

This question asks whether the wrists position should be fixed. This question is related to question B07*, which asks whether an actuator should be placed to enable wrist movement. 11 of the 17 respondents want the wrist to be fixed, which is in accordance with the answers given to question B07*.

It is a well known anatomical fact that the wrist angle is an important parameter that affects the tension on the finger tendon. Hence, the renewed design of the robot (not described in this paper) has an adjustable-angle wrist fixture, so that, just as in the traditional therapy, therapist can the select a proper angle for the wrist for the therapy. Since this angle is mostly kept fixed during an individual therapy session, a manual adjustment mechanism is preferred.

B10: Material Selection for Connecting the Rings

This question asks which material should be used inside the rings. 12 of the 17 engineers suggest Vectro straps. Hand and finger are easily become dirty and perspiring parts of the body. Because of this, the material has to be washable. Silicon is a good candidate according to four participants. Silicon was considered and tested during the development of the robot, but due to its high compliance the idea was abandoned. By using Vectro straps, its is possible to both wrap the finger and keep it steady inside rings.

While Vectro straps are commonly used in rehabilitation robots, silicon surfaces have the advantage of increasing comfort. We also suggest that all surfaces that touch the patient should be replaceable.

Perspectives of the Health Professionals

The third and final category of questions in the survey are posed to health professionals, specifically doctors specialized in hand surgery and physical medicine and physical therapists. The robot is introduced before the questions, with an explanation of the functions and design characteristics of the robot. There are 20 questions in total in this category, posed to 18 health professionals. Some of the questions were answered by only a subset of the group. Questions C02a*, C02b*, C02c*, C04*, C08* and C20* are quantitative questions, and their summary statistics were presented earlier. The remaining questions are all open-ended questions with qualitative answers, and are given in Appendix D of the supplementary document [16]. The findings from both quantitative and qualitative questions are summarized here.

Firstly, the answers to the *quantitative* questions will be discussed:

C02* consists of three parts: C02a* asks about freedom of movement of the robot. 11 of the participants suggest maximal freedom of movement, four suggest limited movement, and three did not answer the question as they first wanted to test the robot on a patient. C02b* asks about the tightness of the robot. 11 of the participants suggest that robot should fit the hands of the patient with a medium tightness, four suggest tight fit, and three expressed no opinion. C02c* asks the angle of the arm to the ground. 10 of the participants suggest 180, four of them 135, one suggest 90 degree angle, and three express no opinion.

C04* asks about the importance of ergonomics in a rehabilitation robot. All of the participants give importance or high importance to the ergonomics of the robot.

C08* asks whether a therapist should assist the patient while patient is exercising with robot. General idea is that a therapist should assist the patient.

C20* asks as if it is important for the robot to be antibacterial. 10 of the respondents think that it is highly necessary, while six find it unnecessary.

Secondly, the answers to selected *qualitative* questions will be discussed:

C01 asks about the fixation of the wrist, and is related to questions B07* and B09. The health professionals were asked if the wrist should be fixed or allowed to move. The answers of show the same distribution as the engineers. 10 professionals suggest that the wrist should be fixed, and two suggest that it should move partially.

C05 asks about the risk factor of the robot. According to doctors and therapists, the most important risk factor for the robot is the risk of causing tendon rupture. The other risks are listed in the supplement [16].

C06 asks how to the safety of the robot can be maximized. Adjustability is listed as the most important factor in increasing safety.

C11 asks about the issues that require special attention during the therapy. Preserving the consciousness of the patient, ensuring hygiene, and respecting pain thresholds constitute the majority of the answers.

C13 asks if the extension and flexion exercises should be part of the therapy. Definite answer is "Yes", with two professionals conditioning the exercises on the healing of the tendon.

Correlation Analysis

A correlation analysis provides insights into the independence of the quantitative (numeric) input variables [17]. While correlation analysis is an integral part of exploratory analysis of data, it is also important since it guides the successive steps in statistical analysis and modeling. In this paper, correlation analysis is used only for exploratory purposes. A positive correlation refers to strong positive relation between the two variables, indicating that increasing values in the first variable are typically accompanied with increasing values in the second.

Appendix E in the supplementary document [16] presents the correlation plot and the correlation matrix, showing the correlations between every pair of quantitative questions. The Appendix also gives an example scatter plot, which demonstrates the high positive correlation between two selected variables.

Top 4% of the positive correlations and top 2% of the negative correlations are displayed in Table 3. Some of the insights from the table are as follows:

⋄ The highest positive correlation of 0.88 is observed between B02* (direct drive & capstan) and B05* (thickness of 2mm). These questions are questions with strong consensus among the engineers, and the strong correlation indicates the consistent approval of the engineers with the two different design dimensions. The strong correlation between B01* and B02* can also be interpreted in the same way.

Table 3: QUESTION PAIRS WITH THE HIGHEST POSITIVE OR NEGATIVE CORRELATIONS

Question1	Question2	Correlation
B02*	B05*	0.88
A03a*	A03c*	0.84
B01*	B02*	0.80
A03c*	A03i*	0.79
A03a*	A03i*	0.77
A03h*	B02*	0.75
A01*	C04*	0.72
A03f*	A03g*	0.71
A03a*	A03b*	0.71
A03h*	B05*	0.69
A03d*	B05*	-0.46
A03e*	B07*	-0.46
A03g*	C08*	-0.47
A03f*	B07*	-0.50
C02a*	C20*	-0.56

◇ There is very strong correlation (0.84) between A03a* (importance of the robot's portability) and A03c* (importance of the robot's weight). Portability and weight are related with each other in design, and the correlation analysis shows that the respondents who consider portability important also consider weight important. So, in their mental models, portability is mainly driven by weight.

◇ There is strong positive correlation between A03i* (comfort) and both A03a* (portability) & A03c* (weight), in addition to the above. This shows that the respondents associate comfort with portability and weight. Thus, these three design requirements should be considered together.

◇ The highest negative correlation of -0.56 is observed between C02a* (freedom of movement of the robot) and C20* (importance of antibacterial material for rings). The health professionals are selecting only *one* of these as important, rather than both.

◇ The next highest negative correlation is between A03f* (durability) and B07* (adding an actuator for the movement of the wrist). The engineers who emphasize durability oppose the idea of adding the additional actuator, even though it would bring extra flexibility during the therapy.

Comparison of Engineers and Health Professionals

The final analysis is the comparison of the responses of engineers and health professionals to the common questions. For this, the nonparametric *Wilcoxon Rank Sum Test* will be used. When data are nonnumeric but are ranked as in ordinal-type data, or when the number of observations is small, "methods based on ranks are often the most powerful ones available" [17].

The result of the test will be the *p-value*, which is the smallest significance level at which the (conservative) null hypothesis H0 would be rejected. This

Table 4: RESULTS OF THE WILCOXON RANK SUM TEST

QuestionID	Question	*p-value*	Mean(Eng)	Mean(HP)
A01*	Positive impact on treatment	0.21	3.12	3.39
A02*	Speeding up the treatment	0.72	3.41	3.17
A03a*	Portability	0.59	4.53	4.22
A03b*	Ease of setup	0.14	3.76	4.11
A03c*	**Weight**	**0.06**	**4.71**	**4.06**
A03d*	Cost	0.99	4.24	4.11
A03e*	Maintainability	0.63	3.65	3.83
A03f*	Durability	0.39	4.47	4.17
A03g*	Safety	0.73	4.65	4.50
A03h*	Adjustable components	0.65	4.06	4.22
A03i*	Comfortability	0.60	4.47	4.28
A04*	Appearence for patient	0.92	2.76	2.83
A05*	**Silent operation**	**0.05**	**3.47**	**2.89**

test statistic will be used to help make the decision in the hypothesis test. If the *p-value* is in the critical region, which is being less than $p = 0.05$, then the null hypothesis H0 will be rejected. Otherwise, H0 will be accepted.

The test is performed on the two specified samples. The null hypothesis H0 is that the distributions are the same (i.e., there is no shift in the location of the two distributions) with an alternative hypothesis H1 that they differ on location (based on median). This test does not assume that the two samples are normally distributed but does assume they have distributions of the same shape. The two samples come from the quantitative common questions grouped by profession, with groups being *engineers* and *health professionals*.

Table 4 displays the results of the test applied for each quantitative common question. The *p-value* of each test is given in the third column, and is compared against $p = 0.05$. There is a statistically significant difference between the opinions of the two groups regarding the importance of "Silent operation" (A05*). Engineers give much higher importance (mean of 3.47) to silent operation compared to health professionals (mean of 2.89).

The *p-value* for "Weight" (A03c*) is also very low, 0.06, almost falling in the critical region. Thus, even though the null hypothesis is not rejected, there is strong statistical evidence towards difference of opinions regarding the weight of the robot. Again, engineers seem to care much more about weight compared to health professionals.

These differences may be explained by the fact that health professionals are used to operating medical devices that are bulky and do not necessarily operate silently. Engineers might be biased through a more "consumer-oriented" point of view.

In Appendix F of the supplementary document [16], the respondents are mapped according to the "distances" between them. The distances are computed according to the Euclidean norm, based on the respondents' answers to the quantitative questions. Overall, there does not seem to be a significant distinction between the two groups. Thus, using all the answers in computing the distances masks the differences in the questions A03c* and A05*.

QUALITY FUNCTION DEPLOYMENT (QFD)

The final contribution of this paper is the construction of the standard *Quality Function Deployment* (QFD) chart to guide the design revisions of the robot. The QFD chart (also referred to as the *House of Quality* (HOQ)) is a visual tool for systematically mapping the customers requirements (wants, expectations and needs) and the functional requirements (engineering metrics). The QFD chart transforms the voice of customers (VOC) into technical metrics. These are done by conducting market surveys, gathering other data, paying attention on customers complaints and evaluating competitors products. In this paper, the survey was conducted to collect the data for the QFD chart, which is shown in Figure 3.

QFD shows the relation between WHATs (customers voice) and HOWs (engineering metrics) in the central matrix. These relationships are *strong relationship* (9), *moderate relationship* (4) and *weak relationship* (1). Next, weights for each of the WHATs are set according to their importance levels. In our study, the weights were determined based on the survey results.

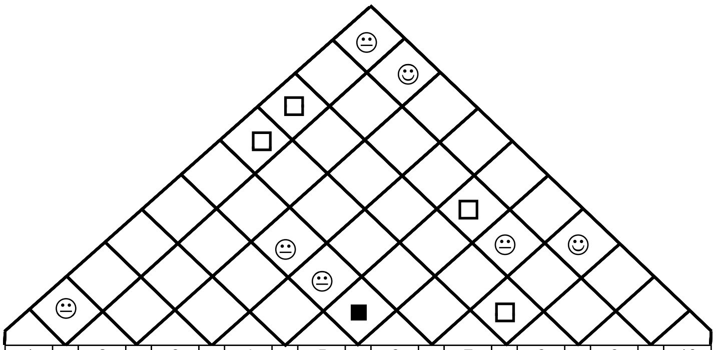
The roof of the chart shows the correlations between the HOWs, with one of four possible symbols. These symbols denote *strong positive, positive, negative,* and *strong negative* correlations.

As a result of QFD analysis, weight is identified as the most important requirement to focus on. Weight affects the patients comfort, and the portability and durability of the robot. Following weight, adjustability of finger holes material, durability and back-driveability have the same level of relative importance. The least important priority is the tensile strength of the links material. The reason is that aluminum is thought to be the most appropriate and processable material on market now, and is already used in the robot.

CONCLUSIONS AND FUTURE RESEARCH

This is the first survey-based study that simultaneously considers the voice of engineers and health professionals in the assessment of a rehabilitation robot. A systematic approach was followed for the assessment of the robot's design, involving a structured survey, quantitative and qualitative analysis of survey results, execution of formal statistical tests, construction of the QFD chart, and the improvement of the robot in the light of the suggestions.

The presented survey has provided us with insights on the priorities of the engineers and health professionals and suggestions on how the current design can be improved. Following the survey, several modifications have been made to the robot: The wrist angle has been made adjustable, so that the therapist can customize the wrist angle for each patient. The installation of the robot has been made more practical by making the parts that touch the hand changeable and hygienic. Avoiding injuries is a very high priority for health professionals, and thus new force and position sensors have been added to the robot to track the state of the robot and the hand. Since weight is an important design requirement



			1	2	3	4	5	6	7	8	9	10
				▲			▼		▼	▼		▲
Relative Weight	Weight / Importance	HOWS / WHATS	Thickness of Links (mm)	Tensile Strength of Links' Material (N)	Adjustability of Finger hole's	Power of Actuator (Watt)	Friction of Bearings (N)	Angle of Flexion	Weight (gr)	Raw Material Cost (TL)	Backdriveability	Durability
7.7	3.0	Easy to Carry							⊗			Θ
10.3	4.0	Light Weight	Θ						⊗			
10.3	4.0	Assembly			⊗				Θ		o	
10.3	4.0	Cheap	o		o	Θ				⊗		
7.7	3.0	Maintenance/Repair		Θ								⊗
12.8	5.0	Comfort			Θ			⊗	⊗		⊗	o
12.8	5.0	Adjustable Parts			⊗		Θ	Θ	o			Θ
7.7	3.0	Durability	Θ	Θ					Θ			⊗
12.8	5.0	Safety				o					⊗	Θ
7.7	3.0	Noiselessness				⊗	Θ					
		Target of Limit Value	2 (mm)		5 (mm)	380 (watt)	0.01 - 0.1 (N)		525 (gr)			
		Difficulty *	8	6	7	7	5	8	9	7	8	9
		Max Relationship Value	3	3	9	9	3	9	9	9	9	9
		Weight / Importance	64.1	46.2	256.4	112.8	61.5	153.8	343.6	92.3	241.0	251.3
		Relative Weight	3.9	2.8	15.8	7.0	3.8	9.5	21.2	5.7	14.8	15.5

* (0=easy to accomplish, 10=extremely difficult)

☺	Strong Positive Correlation
😐	Positive Correlation
□	Negative Correlation
■	Strong Negative Correlation

⊗	Strong Relationship - 9
Θ	Medium Relationship - 4
o	Weak Relationship - 1

Figure 3: HOUSE OF QUALITY FOR THE TENDON REHABILITATION ROBOT

from an engineering point of view, and since it affects portability (which is important for both groups), the weight of the system has been reduced, while the torque of the actuator has been increased. Thus, the insights from the survey have been influential in improving the robot's design, and for confirming the suitability of the changes made independent of the survey results.

Future research in the field can fuse data from the usability test and user surveys in guiding the design of the robot. Meanwhile, having obtained the design requirements and their weights, systematic invention methods such as TRIZ can be applied for improving the design. Another path of research is devising multi-criteria decision analysis (MCDA) techniques for selecting among alternative designs and for guiding new designs. Rehabilitation robots have significant potential to improve the quality and decrease the cost of health care, and product design methodologies are essential in designing such robots, as demonstrated in this paper.

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