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Evaluation of Proprioceptive Sense of the Elbow Joint with RehabRoby

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Abstract— **In recent years, robot-assisted rehabilitation systems have been an active research area that can quantitatively monitor and adapt to patient progress, and ensure consistency during rehabilitation. In this work, an exoskeleton type robot-assisted rehabilitation system called RehabRoby is developed. A control architecture, which contains a high level controller and a low level controller, is designed for RehabRoby. Proprioceptive sense of healthy subjects has been evaluated during the execution of a task with RehabRoby. Additionally, usability of RehabRoby has been evaluated using a questionnaire.**

Keywords- Robot-assisted rehabilitation system, exoskeleton robot, control architecture, proprioception

I. Introduction

There are over 650 million people around the world with disabilities. Although it is accepted as 10% of the whole world population, it is 15.7% in Europe, 12% in USA [1] and 12.29% in Turkey [2]. Physical disability, which occurs by birth or acquired during the life span of the person due to the diseases or a trauma to the central nervous system or musculoskeletal system, affects the functionality of people. The partial or complete involvement of the body such as hemiplegia, quadriplegia, paraplegia, monoplegia in regard to the variety of the conditions such as stroke, cerebral palsy, spinal cord injuries or spina bifida may result with functional deficits of the upper or lower extremities as well as the trunk.

The physical therapy and rehabilitation programs are applied to the people with disability to increase their joint range, strength, power, flexibility, coordination and to improve their functional capacity as well as their level of independence [3],[4]. In recent years, robot-assisted rehabilitation systems have become an active research area in rehabilitation programs [5]-[10]. End-effector based such as MIT-MANUS [5], MIME [6] and GENTLE/S [7] or exoskeleton type robots such as ARMin [8], T-WREX [9], and Selford Rehabilitation Exoskeleton [10] have previously been developed to provide assistance to patients during the execution of upper-extremity rehabilitation exercises. It has shown that robot-assisted rehabilitation can improve motor outcomes, degree of recovery and sensory motor stimulation of stroke patients [11]-[14]. Although robot-assisted rehabilitation systems are mostly utilized in stroke rehabilitation, they can also be considered as a treatment modality after the orthopedic and other neurologic conditions [15]. Recent studies revealed significant benefits of repetitive robot-assisted therapy in people with chronic motor impairments [16]-[18]. However, to our knowledge the evaluation of proprioception of upper extremity has not been evaluated with robot-assisted rehabilitation systems before. The evaluation of proprioception is an important issue, because the success of functional joint movements depends on the kinesthetic sense of the person, which is related with the proprioception sense of the musculoskeletal structures of the joints [19].

Proprioception, which is the ability to sense the position and location of the joints, is generated by multiple sensory receptors such as muscle spindle, tendon and joint receptors. Evaluation of joint proprioception is traditionally realized by determining joint position sense or perception of joint movement (kinesthesia) [20]. Joint position sense is assessed by measuring the ability of the person to reproduce a predetermined angle in the range of motion of the joint. The difference between the predetermined angle and person's angle is considered as error score or error of matching. Note that proprioception may change in different circumstances such as gender, training or fatigue [21]-[23]. Thus, assessment of joint proprioception in patients having neuromuscular disability may provide us a better understanding in the treatment and the assessment of the precise movements during rehabilitation programs. It has also previously shown that repeated active exercises have a positive influence not only on motor deficits, but also on defective proprioception [24]. Thus, robot-assisted rehabilitation systems can be used to provide repetitive exercises to improve the proprioception [25]. In this study, we only investigate if a robot-assisted rehabilitation system RehabRoby can be used to evaluate proprioception of the elbow flexion of healthy subjects in different circumstances.

Subjects are asked to perform elbow flexion with RehabRoby when their eyes are open and close. They are forced to rely on proprioception alone to successfully achieve the goal when they close their eyes. Additionally, usability of RehabRoby has been evaluated via a questionnaire in order to decide if a robotic system "RehabRoby" can be further possibly used to provide training of functional activities to the patients. Note that this is a feasibility study for the proposed robotic system RehabRoby to be used in the future to assess the proprioception of patients with neuromuscular diseases.

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II. METHODS

A. Control Architecture

A control architecture is developed for robot-assisted rehabilitation system RehabRoby to complete the rehabilitation tasks in a desired and safe manner (Fig. 1). Control architecture consists of a high-level controller, a low-level controller, a robotic system RehabRoby and a sensory information module. High level controller is responsible to monitor the progress, to understand the effects of the treatment program using sensory information module, to take into account therapist's decision about the task, to decide the plan of action and to send the desired task trajectories to the low-level controller. A hybrid system modeling technique is used to design the high-level controller [26]. Impedance control with robust position control is used as the low-level controller to provide assistance to the patients to complete the rehabilitation task in a desired manner with RehabRoby.

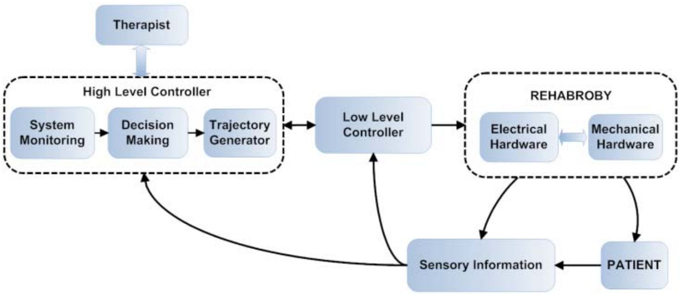

Figure 1. Control Architecture of the RehabRoby

B. Experimental Set-Up

RehabRoby has been designed to provide extension, flexion, abduction, adduction, rotation, pronation and supination upper-extremity movements and also combination of these movements for activities of daily living. The placements of the shoulder and elbow joints in RehabRoby are similar to ARMin III [8] except the ergonomic design of the vertical displacement of the glenohumeral (GH) joint in ARMin III has not been considered in design of RehabRoby. RehabRoby has been designed in such a way that it can be easily adjustable for people with different arm lengths. Anthropometric approaches have been used during the design of RehabRoby. The human arm lengths have been selected as the basis for the link lengths of the RehabRoby. The values given include the measurements of the arm lengths of 2100 people in 14 cities in Turkey. RehabRoby can also be used for both right and left arm rehabilitation. RehabRoby can be translated from right arm use to left arm use with the following steps, i) RehabRoby is rotated 90^0 about θ_2, ii) Then RehabRoby is rotated 180^0 about θ_1, and iii) RehabRoby is rotated -90^0 about θ_2.

RehabRoby has been interfaced with Matlab Simulink/Realtime Workshop to allow fast and easy system development. Humusoft Mf624 model data acquisition board is used to provide real time communication between the computer and the other electrical hardware. A 19" LCD screen is positioned right in front of the subject at a distance of about 1 m to display his/her motion.

Figure 2. Subject with RehabRoby

An arm splint has been designed and attached to RehabRoby. It has the humeral and forearm thermoplastic supports with velcro straps and a single axis free elbow joint (Fig. 2). A thermoplastic inner layer covered by soft material (plastazote) is used due to the differences in the size of the subjects' arms. Thus, the total contact between the arm and the splint is achieved as much as possible to eliminate loss of movement during the execution of the task. The force sensor is placed in the inner surface of the thermoplastic molded plate attached dorsally to forearm splint via velcro straps. Kistler model press force sensor (9313AA1), which has a quite small size, is selected to measure contact forces between the subject and RehabRoby. This arrangement is required to provide a firm contact between the dorsal surfaces of the forearm and the force sensor during the elbow joint flexion. The force value recorded from the force sensor is obtained using a Humusoft Mf624 data acquisition card with a sampling rate of 500Hz.

Ensuring safety of the subject is a very important issue when designing a robot-assisted rehabilitation system. Thus, in case of emergency situations, the physiotherapist can press an emergency stop button to stop the RehabRoby (Fig. 2). The motor drivers of RehabRoby can be disabled separately or together by pressing the driver enable/disable buttons without disconnecting the energy of the robotic system in any case of emergency situations. The power of the system is supported with uninterruptible power supply, thus, there is no power loss in the system, and RehabRoby will not collapse at any time. Additionally, rotation angle and angular velocities of each joint of RehabRoby are monitored by the high-level controller to disable the robot motion in case of the out of limits.

III. Experiments

A. Task Design

The objective of this study is to investigate the proprioception of university students according to their occupation. One group of students has electrical and electronics engineering-EEE background and the other group of students are physiotherapy-PT students. Since these two groups have different awareness of body image and kinesthetic sense due to their educational interest, we thought that proprioception sense can be different between EEE and PT students. Additionally, we aimed to evaluate usability of RehabRoby. Elbow flexion movement was chosen for the initial study because of the usage sequence during all day [27]. Furthermore, elbow flexion is commonly used in the rehabilitation of upper extremity as a daily living activity to perform the tasks [28]. This study has been approved by the Institutional Review Board of Yeditepe University Hospital (IRB #032).

B. Experiment Protocol

1) Preparation of the Subjects:

Subjects were seated in the height adjustable chair as shown in Fig. 2 and their arms were placed in the splint tightly secured with velcro straps. The height of the chair was adjusted for each subject to start the task in the same arm configuration. The arm is positioned at extension and slight abduction, elbow is at extension, and pronation, the hand and the wrist were free at neutral position. In the first experiment, RehabRoby had been kept passive and subjects were required to flex their elbows actively (isotonicly) to reach the desired degrees. In the second experiment, subjects were asked to flex their elbows to reach the same desired degrees with a comfortable resistance applied by RehabRoby.

2) Assesment of Proprioception

Subjects were asked to flex their elbow joints actively and also against a comfortable resistance for 20^0, 45^0 and 90^0, respectively. This comfortable resistance applied by RehabRoby was selected by each subject at the beginning of the experiment. Although, in [27] it has been mentioned that the elbow joint range of motion is to be practical in 0-160°, we have selected 20°, 45° and 90° of flexion angles as target angles for our study. The test protocol had been explained to the subjects in details, and then subjects were asked to practice with RehabRoby for 5 minutes to become familiar with the movement and the target angles that were shown in the monitor. The test protocol consisted of two steps. In the first step, subjects were asked to look at the monitor (with visual feedback-wVF) while they were flexing their elbows three times actively (subject active/robot passive-SARP), and then three times against the comfortable resistance (subject active/robot resistive- SARR) for 20^0, 45^0 and 90^0. In the second step, the subjects were asked to close their eyes and repeat the same procedures (SARP – SARR) three times without visual feedback- woVF. The subject's movement and their applied forces were recorded. The subjects took a 3-5 minutes break between the sessions. Each experiment did not last more than half an hour.

C. Subjects

Totally twenty (20) subjects with two groups as electrical and electronics engineering-EEE (n=10, Male/Female: 5/5) and physiotherapy-PT (n=10 Male/Female: 5/5) students of the Yeditepe University were participated in the study. None of them had any motor impairment in their arms. All subjects were right handed except one.

The results were expressed as means ±SD. Mean age of the subjects was 21,95 ±3,58 years for total group, 20,40±3,50 years for PTS , 23,50±3,06 years for EEES their body weight was 67,85 ±12,93 kg for total group, 69,40±13,30 kg for PTS , 66,30±13,06 kg for EEES , height was 1,73 ±0,08 m. for total group, 1,73±0,89 m for PTS, 1,73±0,78 m for EEES and body mass index-BMI (kg/m²) was 22,60 ±3,00 kg/m² for total group. Subject's physical activity/sport habits and general health history related with their upper extremity were surveyed. Through the whole group 6(%30) of the individuals were attending sports (all of the 6 were PTS students), 2(%10) had surgery history (all of the 2 were PTS), 2(%10) had chronic diseases all of the 2 were PTS) and finally 1(%5) of the participants were using regular medication (this volunteer was a PTS).

D. Evaluation Techniques

Besides the proprioceptive assessment of the subjects, the sociodemografic evaluation (weight, height, dominancy, sports attendance, chronic diseases, injury of the upper extremities, regular medication) was done with a questionnaire specially prepared for this study. Goniometric tests of elbow joint flexion, extension and rotations (pronation- supination) and Myometric Test (JTech Dynomometry- poundmeter) of elbow flexor (M. Biceps Brachii), extensor (M. Triceps brachii), rotators (pronator-supinators) were realized to understand the physical condition of the subjects.

Three questionnaires were given to subjects to get feedback about the usability of the RehabRoby. One of them was designed for the assessment of technical application of the RehabRoby. The questions were assessed from 1 to 5 points (1: Strongly Disagree, 2: Disagree, 3: Neutral, 4: Agree, 5: Strongly Agree) (Table I). The two other questionnaires were Perceived Rate of Exertion-PRE and Visual Analog Scale-VAS. VAS scale changes from 0 to 10. The difficulty level changes from 6 to 20 in PRE.

TABLE I: The questionaire for the assessment of technical application of the RehabRoby

		1	2	3	4	5
Q1	RehabRoby is a safe system	□	□	□	□	□
Q2	RehabRoby can be easily mounted	□	□	□	□	□
Q3	RehabRoby use is easy	□	□	□	□	□
Q4	RehabRoby gives fast response to my requests	□	□	□	□	□
Q5	RehabRoby's speed is suitable	□	□	□	□	□
Q6	RehabRoby can be used for physical therapy	□	□	□	□	□
Q7	I feel no pain after I use RehabRoby	□	□	□	□	□
Q8	RehabRoby's sensors are comfortable	□	□	□	□	□
Q9	I am scared when I use RehabRoby	□	□	□	□	□
Q10	I feel tired after performance of the task with RehabRoby	□	□	□	□	□

E. Statistically Analysis

Statistical analyses were performed using SPSS software package program (Version 16.0, SPSS). Wilcoxon and Mann–Whitney non-parametric tests were used for one-time comparisons within and between the groups for paired and unpaired data, respectively. The course of a variable within a specific group of subjects was compared using the Wilcoxon test for paired samples. Pearson's correlation coefficients were calculated to investigate the correlations between the effect of gravitational and resistive forces on proprioception and also between the values acquired with visual feedback and without visual feedback. The level of statistical significance was set at $p < 0.05$.

IV. RESULTS

Initially, mean and standard deviation of the proprioception perception errors between the target angles as 20^0, 45^0 and 90^0 and subject's performed angles (degree) had been calculated for each subject. We had found that the error of matching of PTR (X=-0.31±0.31) were significantly lesser than the EEES (X=-0.77±0.59) (PTS rank=13.45; EEES rank=7.55; u=20.50, $p<0.05$) (Table II).

TABLE II: THE MEAN VALUES OF ERROR OF MATCHING AT 20°, 45°, 90° WITH/WITHOUT VISUAL FEEDBACK (W/WOVF) FOR BOTH GROUPS

	Target Angles	Error during Subject Active/ Robot Passive (SARP)			
		wVF (°) X±SD	woVF(°) X±SD	Z	P
PTS	20°	-0,12±0,27	-4,74±6,19	-2,191	**0,028**
	45°	-0,20±0,36	-3,42±8,93	-1,376	0,169
	90°	-0,51±0,60	5,44±11,56	-1,784	0,074
EEES	20°	-0,60±1,12	-4,76±2,84	-2,497	**0,013**
	45°	-0,53±0,64	-4,42±5,48	-2,293	**0,022**
	90°	-0,33±0,52	-2,27±7,63	-0,663	0,508
Total	20°	-0,36±0,84	-4,74±4,69	-3,397	**0,001**
	45°	-0,37±0,54	-3,93±7,23	-2,539	**0,011**
	90°	-0,42±0,56	1,59±10,33	-0,859	0,391
	Target Angles	Error during Subject Resistive/ Robot Resistive (SRRR)			
		wVF (°) X±SD	woVF(°) X±SD	Z	P
PTS	20°	-0,67±3,70	-4,68±3,08	-2,701	**0,007**
	45°	-0,31±0,31	-3,79±4,44	-2,191	**0,028**
	90°	-0,72±0,33	1,00±4,24	-0,866	0,386
EEES	20°	-2,65±4,11	-4,14±2,84	-1,682	0,093
	45°	-0,77±0,59	-7,05±7,17	-2,701	**0,007**
	90°	-0,80±0,31	-3,56±8,52	-1,172	0,241
Total	20°	-1,67±3,02	-4,41±2,90	-3,099	**0,002**
	45°	-0,55±0,52	-5,42±6,04	-3,435	**0,001**
	90°	-0,76±0,61	-1,28±6,96	-0,411	0,681

SARP: Subject active/robot passive, SARR: Subject active/robot resistive, wVF: with visual feedback woVF: without visual feedback

The relationship between physical properties (M.Biceps Brachii strength, elbow flexion ROM, Cubital Angle) and the sport/regular physical activity interest of the whole subjects with the error of matching to the target angles at 20º, 45º, 90º during active (SARP) and resistive (SRRR) elbow flexion with and without visual feedback (wVF and woVF) were also analyzed. A positive correlation relation between M. Biceps Brachii strength and error of matching of the resistive elbow flexion with visual feedback (SARR wVF) at 45º (r= 0,458, $p<0.05$) and without visual feedback (SARR woVF) at 20º (r=0.463, $p<0.05$) was found.

The relationship between the torque of the subjects at 20^0, 45^0, 90^0 and proprioception perception errors during w/woVF had been evaluated. Table III presented the positive correlation relationship between the torque and the error of matching during active elbow flexion (SARP) (r=0.466, $p<0.05$) and also a negative correlation relationship during resistive elbow flexion (SARR) while eyes were closed that is without visual feedback (woVF) (r=-0.546, $p<0.05$) at 20^0 of angle.

TABLE III: THE RELATIONSHIP BETWEEN TORQUE AND ERROR OF MATCHING AT 20°, 45°, 90° IN BOTH GROUPS

Task to Perform	Target Angles	r	p
SARPwVF	20^0	0.272	0.246
	45^0	-0.104	0.663
	90^0	-0.089	0.710
SARPwoVF	**20^0**	***0.466***	***0.038****
	45^0	0.008	0.975
	90^0	-0.202	0.394
SARRwVF	20^0	-0.366	0.113
	45^0	-0.325	0.162
	90^0	-0.026	0.915
SARRwoVF	**20^0**	***-0.546***	***0.013****
	45^0	-0.162	0.494
	90^0	-0.223	0.359

SARP: Subject active/robot passive, SARR: Subject active/robot resistive wVF: with visual feedback, woVF: without visual feedback; * ($p<0.05$)

The effects of visual feedback on the proprioceptive perception during active (SARP) and resistive (SARR) elbow flexion had also been evaluated. The error in proprioceptive perception was significantly higher in both application (SARP and SARR) without visual feedback (woVF) at 20^0 and 45^0. However, this was not significant for the values at 90^0 in both situations (Table IV).

TABLE IV: EFFECT OF VISUAL FEEDBACK ON ERROR OF MATCHING FOR BOTH STUDENT GROUPS

Task to Perform		z	p
SARP wVF-woVF	**20^0**	-3.397	***0.001****
	45^0	-2.539	***0.011****
	90^0	-0.859	0.391
SARR wVF-woVF	**20^0**	-3.099	***0.002****
	45^0	-3.435	***0.001****
	90^0	-0.411	0.681

SARP: Subject active/robot passive, SARR: Subject active/robot resistive wVF: with visual feedback, woVF: without visual feedback; * ($p<0.05$)

We have not found any significant relationship between the proprioception perception errors and VAS and PRE. The mean values of VAS and PRE for the usability of the RehabRoby were given in Table V. However, the acceptance of RehabRoby based on the questionnaire was found as 37.10 ± 4.45 (over 50). Questionnaire results for the assessment of technical application of RehabRoby were presented in Table VI.

TABLE V: THE MEAN VALUES OF VAS AND PRE FOR THE USABILITY OF THE REHABROBY

		Task to Perform	VAS and /PRE Results X±SD
VAS	SARP	wVF	2.35±2.22
		woVF	4.48±2.44
	SARR	wVF	3.46±2.38
		woVF	5.10±2.67
PRE	SARP	wVF	10.20±2.98
		woVF	12.50±2.89
	SARR	wVF	11.30±2.83
		woVF	13.5±3.40

SARP: Subject active/robot passive, SARR: Subject active/robot resistive wVF: with visual feedback, woVF: without visual feedback
VAS: Visual Analog Scale, PRE: Perceived Rate of Exertion

TABLE VI: QUESTIONAIRE RESULTS FOR THE ASSESSMENT OF TECHNICAL APPLICATION OF THE REHABROBY

	(1) Strongly Disagree	(2) Disagree	(3) Neutral	(4) Agree	(5) Strongly Agree
Q1	-	-	0,15	0.40	0.45
Q2	-	0.15	0.05	0.40	0.40
Q3	-	000.5	0.15	0.35	0.45
Q4	-	0.5	0.40	0.30	0.25
Q5	-	0.05	0.15	0.40	--0.40
Q6	-	-	0.10	0.35	0.55
Q7	-	0.10	0.15	0.10	0.65
Q8	0.05	-	0.30	0.55	0.10
Q9	0.90	0.10	-	-	-
Q10	0.55	0.20	0.15	0.10	-

V. DISCUSSION AND CONCLUSION

This study presents evaluation of proprioception perception of subjects when they perform elbow flexion task with a robotic device RehabRoby. Since motor impairment is frequently associated with degraded proprioception and somatosensory functions, it is necessary to diagnose and then improve loss of proprioception. In this study, we investigate if a robot-assisted rehabilitation system RehabRoby can be used to evaluate proprioception of the elbow flexion of healthy subjects in different circumstances. Thus, we evaluate the proprioception sense changes of the elbow flexion of healthy subjects via with visual feedback and without visual feedback and with different background. This study can be considered as a feasibility study for the proposed robotic system RehabRoby to be used in the future to assess, diagnose and improve the proprioceptive sense of stroke patients.

It has previously mentioned in [29] that gravitational forces acting on forearm differ according to the position of the elbow (close to vertical at 20°, oblique at 45°, and horizontal at 90°). Thus, torque of elbow joint increases as the forearm positions horizontally because of the increase in gravitational forces. It has previously been pointed out that the forearm position sense is affected by the torque as the angle become steeper. It has also been reported that the error of matching of arm and forearm decreases at 90^0 of flexion when the voluntary contraction is at maximum level due to the increased gravitational forces [29]. However, we have found a negative relationship between the torque and the error of matching of elbow joint only at 20° when subjects perform resistive elbow flexion while their eyes are closed. Although this is a weak relationship, it explains the effectiveness of the muscle torque on the proprioception perception error where the error of matching is decreasing as the muscle torque increases (Table III). On contrary to the results of [29] even if the forearm is close to vertical and faces with less gravitational forces at 20^0, resistive voluntary motion may demand with higher proprioceptive inputs in the elbow joint. Another relationship has been found between the strength of biceps brachii muscle and the error of matching during resistive elbow flexion while subject's eyes are closed at 20° and while their eyes are open at 45^0. This relationship supports the concept of increased demand of proprioceptive inputs.

In this study, the effect of vision on the proprioceptive perception during active and resistive elbow flexion controlled with RehabRoby has been evaluated. It has previously mentioned that proprioception sense predominate the transformation of the spatial information received via vision into the comments that result in muscle force and joint torques [30]. Additionally, it has been demonstrated that both vision and proprioception are combined to some extend for the purposeful and controlled movement [31]. According to our results, the proprioception has been significantly decreased during the active and resistive elbow flexion without vision. Ultimately, these results support the effectiveness of vision on the accuracy of the motor activity.

We have also investigated the relation between the proprioception perception errors and educational interest of subjects. The PT students have less error of matching then the EEE students. This may be due to the increased awareness of body image and kinesthetic sense assimilated during the course of physiotherapy students' education.

In this study, we observe that elbow flexors torque and biceps brachii muscle strength are effective on the proprioceptive sense of the joint. Vision and torque of voluntary movement are important for the accuracy. Additionally, improving the body awareness and education on physiotherapy may improve the proprioception sense of the elbow joint.

A feasibility study about safety and usability of RehabRoby during the interaction with the subjects has been completed with a questionnaire. In the questionnaire, it is noticed that approximately 85% of the subjects agree that RehabRoby is a safe system and 80% of the subjects think RehabRoby can be easily mounted and it is easy to use. 75% of subjects feel no pain and do not feel tired when they use RehabRoby. These results give us a motivation to use

RehabRoby for future rehabilitation therapy tasks for people with disability to improve proprioception. According to the VAS scale the subjects think that the use of RehabRoby is not too easy when they donot have visual feedback and when RehabRoby applies resistive motion during elbow flexion. These may be because of the difficulty of the task when there is no vision and when resistance exists.

As a future study, we would like to investigate if RehabRoby can be used to improve proprioception of the patients. Additionally, we would like to use RehabRoby to assess the functional status, and to train the effected upper extremities of the patients with chronic motor impairments or orthopedic conditions.

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