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Evaluation of elbow joint proprioception with RehabRoby: a pilot study

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Objective: The aim of this study was to evaluate the proprioceptive sense of elbow flexion through a robot-assisted rehabilitation system, RehabRoby, and to understand the usability of RehabRoby as a robotic system in physiotherapy.

Methods: The study included 20 volunteer, healthy students studying either physiotherapy (PT) (5 females and 5 males) or electrical and electronics engineering (EEE) (5 females and 5 males). Using the RehabRoby, they were asked to flex their elbow joints in pronation actively and then against a comfortable resistance to the target angles (20º, 45º and 90º), with eyes open and closed. Angle of movement and applied torque for each target angle and error of movement with respect to the target angle (error of matching) were recorded as absolute values. Participants' socio-demographic and physical features were also evaluated.

Results: Physiotherapy students had less matching error at 45º with eyes opened than EEE students. A negative correlation was found between resistive elbow flexion and applied torque while eyes closed at 20º ($p<0.05$). Biceps brachii strength and being female were significant predictive factors for the least matching error in active elbow flexion at 20º with eyes closed. Error of matching at 45º without vision was lower in the PT group (-0.31) than in the EEE group (0.77). In addition, it was noticed that biceps brachii muscle strength played an important role in the proprioceptive sense of the motion at 20º.

Conclusion: The RehabRoby can be considered a usable system for the evaluation of joint proprioception sense. With future validity studies, the RehabRoby may be used to assess, diagnose and improve the proprioceptive sense of patients.

Key words: Control architecture; elbow flexion; exoskeleton robot; proprioception; robot-assisted rehabilitation system; torque.

Robot-assisted exercise systems have become an area of active research in rehabilitation programs.[1-11] End-effector-based systems, such as MIT-MANUS,[1] MIME[2] and GENTLE/S[3] or exoskeleton type robots such as ARMin,[4-7] T-WREX,[8] Pneu-WREX,[9] L-Exos,[10] and Selford Rehabilitation Exoskeleton[11] were developed to assist patients in upper-extremity exercises. Robot-assisted rehabilitation has been shown to improve motor outcomes, degree of recovery, and sensory and motor stimulation in stroke patients.[12-17]

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Recent studies have revealed significant benefits of repetitive robot-assisted therapy in patients with chronic motor impairments.[18-20]

The success of functional joint movements depends on the kinesthetic and proprioceptive properties of the musculoskeletal structures of the joints.[21] The diagnosis and improvement of proprioceptive deficiency are important for both clinicians and physiotherapists. Robotic systems have also been shown to improve proprioception in stroke patients.[22] It is assumed that repeated active exercises have a positive influence not only on motor deficits but also on defective proprioception after traumatic injuries or orthopedic operations.[23]

One such exoskeleton robotic system, the RehabRoby, can provide assistance to patients during therapy exercises. The RehabRoby is designed to assist patients during single joint movements (elbow flexion, shoulder abduction), such as reaching for a cup, and multi joint movements such as hair combing and face washing.

The aim of this pilot study was to evaluate the proprioceptive sense of healthy participants in order to provide clues on how the proprioceptive sense affects the functions of participants using the RehabRoby. Additionally, we aimed to investigate the usability of the RehabRoby for the rehabilitation of the functional activities that may require fine shoulder/elbow coordination.

Materials and methods

The proprioceptive sense of the volunteers was evaluated during the execution of dominant elbow joint flexion in pronation, both actively and against a comfortable resistance to replicate the reference-target angles (20º-45º-90º) using the RehabRoby system. The study included 20 students (mean age: 21±3.5 years) studying either physiotherapy (PT) or electrical and electronics engineering (EEE). Each group had 10 students (5 females and 5 males). Mean body weight was 67.85±12.93 kg, height was 1.73±0.08 m, and body mass index (BMI) was 22.60±3.00 kg/m^2 (Table 1). Physical activity interests and health history in relation to their upper extremities was taken (Table 2). The right hand was dominant in 19 participants and the left in one.

A questionnaire was used to assess socio-demographic information (weight, height, hand dominance, participation in sports and/or physical exercise, chronic diseases, injury of the upper extremities, regular medication). Elbow joint flexion, extension and rotation (pronation and supination) tests using a goniometer and elbow flexor (biceps brachii, brachialis), extensor (triceps brachii) and rotator (pronator-supinators) tests using the Myometric Test (JTech Dynamometer®; JTech Medical, Salt Lake City, UT, USA) were performed to assess the physical condition of the participants.

The RehabRoby is designed to provide upper-extremity movements (Fig. 1). Range of motion (ROM), joint torques, velocities and accelerations for RehabRoby have been determined using the measurements of the movements of a healthy participant during two activities of daily living (ADL) tasks (drinking soup and coffee).[4,5] The control architecture was developed to take into account therapist decisions, to decide on the plan of action and to provide assistance to patients to complete a rehabilitation task.[24,25]

RehabRoby has been interfaced with MATLAB Simulink/Realtime Workshop to allow fast and easy system development. A Humusoft MF624 model data acquisition board is used for communication of the computer and electrical hardware. Maxon models of brushed direct current (DC) motors are selected to actuate the joints of the RehabRoby. High-resolution digital incremental encoders are coupled with DC motors to obtain high accuracy in joint position measurements. All experiments were performed in a room where the temperature ranged between 20º and 25º C. This room temperature is convenient to obtain consistent performance in electrical and mechanical parts of RehabRoby. A 19-inch LCD screen was positioned in front of the participant at a distance of about 1 m to display the movements.

Table 1. The mean values of age, height, weight and BMI of the subjects.

	Age (yrs)	Height (m)	Weight (kg)	BMI (kg/m^2)
PTS (n=10)	20.40±3.50	1.73±0.89	69.40±13.30	23.14±3.00
EEES (n=10)	23.50±3.06	1.73±0.78	66.30±13.06	22.59±3.00
Total (n=20)	21.95±3.58	1.73±0.08	67.85±12.93	22.60±3.00
	F: 0.003	p: 0.957	F: 0.910	p: 0.353
	F: 0.081	p: 0.779	F: 0.000	p: 0.984

PTS: physiotherapy students; EEES: electrical-electronics engineering students

Table 2. The physical activity interest and health history related with upper extremity.

	PTS (n=10)		EEES (n=10)		Total (n=20)	
	Yes	No	Yes	No	Yes	No
Sports attendance	6	4	0	10	6	14
Operation	2	8	0	10	2	18
Chronic diseases	2	8	0	10	2	18
Regular medication	1	9	0	10	1	19

PTS: physiotherapy students; EEES: electrical-electronics engineering students

The thermoplastic arm splint designed for the RehabRoby has humeral and forearm supports with velcro straps, and a thermoplastic inner layer that is covered by a soft material (Plastazote®). A force sensor (Kistler-9313AA1; Kistler France, Les Ulis, France) was placed in the inner surface of the dorsal plate attached to the forearm splint. The speed of the movement controlled by the RehabRoby was in the range of 5°/sec.

This study was approved by the Institutional Review Board of Yeditepe University Hospital (IRB #032). Participants were informed about the experiment protocol and an orientation was given.

Fig. 1. Participant with RehabRoby. [Color figure can be viewed in the online issue, which is available at www.aott.org.tr]

Participants were seated in the height-adjustable chair. The shoulder joint was positioned at extension and abduction (10º) and the elbow at extension and supination. Since the movement was an open kinetic loop, the hand and the wrist were left free in a neutral position.

Elbow range of motion degrees for ADL have been defined in the literature of 16º to 123º.[26-28] We used the most commonly used ADL elbow joint angles of 20º, 45º and 90º for activities such as putting a fork to the mouth (45 to 90º) and carrying a weight (16 to 30º).[27]

The amount of comfortable resistance was defined using an admittance controller.[25] Resistance value varied according to changes in the velocity and acceleration of the motion (maximum and minimum resistance was 2.75 Nm and 0 Nm, respectively).

Initially, participants were required to flex their elbows actively (isotonic) to reach the target angle (TA) (participant active/robot passive-PARP). Then participants repeated the same ipsilateral matching against a comfortable resistance applied by the RehabRoby (participant active/robot resistive-PARR). Each participant was asked to monitor the graphic (with visual feedback [wVF]) while flexing their elbows. Later, participants were asked to close their eyes (without visual feedback [woVF]) and repeat the same PARP and PARR protocol.

Movement angle, the applied torque in each angle and the error of movement with respect to the TA (error of matching)[29] were recorded. Each participant had breaks of 3 to 5 minutes between trials. Each experiment took less than 30 minutes.

Participants completed 3 questionnaires on the usability of the RehabRoby. One questionnaire was designed for the assessment of technical applicability of the RehabRoby. The Perceived Rate of Exertion (PRE)[30] was applied to understand the amount of exertion the participants felt during the task execution and the Visual Analog Scale (VAS)[31] to assess the amount of difficulty experienced while using the RehabRoby.

The least error of matching of the participants' with and without visual feedback for each angle was recorded. The Wilcoxon and Mann-Whitney U tests were used for comparisons within and between the groups for paired and unpaired data using SPSS v.16.0 software (SPSS Inc., Chicago, IL, USA). The course of a variable within a specific group of participants was compared using the Wilcoxon test for paired-samples. Pearson's correlation coefficients were calculated to investigate the correlations between the error of matching to the target angles, and the torque values at each angle during active (PARP) and resistive (PARR) elbow flexion wVF and woVF. Linear regression models were used to determine PARPwoVF, PARPwVF, PARRwoVF, and PARRwVF predictors. P values of less than 0.05 were considered statistically significant.

Results

There were no statistically significant differences for age, weight, height and BMI between PT and EEE students. BMI (normal: 20 to 25.9 kg/m^{2}N) was higher in the PT group (23.14±3.00) than EEE group (22.04±7.69). There was no significant difference between genders with respect to BMI values (p=0.984) and age (p=0.957).

Elbow flexion matching errors for both groups in PARPwVF/woVF and PARRwVF/woVF are presented in Table 3. The wVF minimum matching error 45º was lower in the PT group (-0.31±0.31) than in the EEE group (0.77±0.59) (p<0.05). A positive correlation between biceps brachii strength and the least error of matching during PARRwVF at 45º (p<0.05) and PARRwoVF at 20º (p<0.05) was observed.

There was a positive correlation between the torque and the least error of matching during PARP (p<0.05) and a negative correlation during PARR woVF (p<0.05) at 20º (Table 4).

Proprioceptive perception error was significantly higher in woVF during both PARP and PARR applications at 20º and 45º. However, this was not significant at 90º (Table 5).

In the linear regression analysis, being female (p=0.023, R^2=0.38) and biceps brachii strength (p=0.015, R^2=0.38) were significant predictors of the least error of matching for PARPwoVF at 20º. Cubital angle (p=0.005, R^2=0.54) and biceps strength (p=0.011, R^2=0.54) were significant predictors of the least error of matching for PARRwoVF at 20º (Table 6).

There was no significant relationship between proprioception perception errors and VAS and PRE

Table 3. The mean values of error of matching at 20°, 45°, 90° with/without visual feedback (w/woVF).

Task to perform	Participants	Target angles	Error during elbow flexion			
			wVF (°) X±SD	woVF (°) X±SD	Z	P
PARP	PT	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
	EEE	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
PARR	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

PARP: participant active/robot passive; PARR: participant active/robot resistive; wVF: with visual feedback; woVF: without visual feedback. Bold values indicate p<0.05.

Table 4. The relationship between torque (T) and proprioception perception errors at 20°, 45°, 90° w/woVF.

Task to perform	Target angles	R	p
PARPwVF	20°	0.272	0.246
	45°	-0.104	0.663
	90°	-0.089	0.710
PARPwoVF	20°	0.466	**0.038**
	45°	0.008	0.975
	90°	-0.202	0.394
PARRwVF	20°	-0.366	0.113
	45°	-0.325	0.162
	90°	-0.026	0.915
PARRwoVF	20°	-0.546	**0.013**
	45°	-0.162	0.494
	90°	-0.223	0.359

PARP: participant active/robot passive; PARR: participant active/robot resistive; wVF: with visual feedback; woVF: without visual feedback. Bold values indicate p<0.05.

Table 5. Effect of visual feedback on the error of matching during active (PARP) and resistive (PARR) elbow flexion of all participants.

Task to perform		R	p
PARP wVF-woVF	20°	-3.397	**0.001**
	45°	-2.539	**0.011**
	90°	-0.859	0.391
PARR wVF-woVF	20°	-3.099	**0.002**
	45°	-3.435	**0.001**
	90°	-0.411	0.681

PARP: participant active/robot passive; PARR: participant active/robot resistive; wVF: with visual feedback; woVF: without visual feedback. Bold values indicate p<0.05.

scores. The participants' acceptance of RehabRoby was found as 37.10±4.45 over 50 points. Participants reported that the RehabRoby was difficult to use without visual feedback and with resistive motion during task execution.

Discussion

The proprioceptive sense of healthy participants using the RehabRoby system was evaluated during elbow flexion (0°-160° N) in this study.[32] Our hypothesis was that PT students would have less error than the EEE students due to their increased awareness of body image and kinesthetic sense. Body image is affected by intellectual, psychological and social experiences as well as biology.[33] Thus, PT students were assumed to be more familiar with movement patterns and joint positions.

The contribution of proprioceptive and visual information in controlling the distance of rapid single-joint reaching movements involving the elbow joint has been previously examined.[34] Bagesteiro et. al[34] studied the replication of the elbow joint target angles of 115 and 125 degrees starting from 90, 95, 100 and 105 degrees. Meanwhile, Walsh et al. investigated the effects of fatigue on the position sense of the forearm at the matching angles of 15, 30 and 45 degrees.[35] This study selected the angles of 20, 45 and 90 degrees, as these are frequently used in ADL.

The ability of the subject to match the TA was been evaluated to understand their proprioceptive acuity. Gravitational forces acting on the forearm differ according to the position of the elbow (close to vertical at 20°, oblique at 45° and horizontal at 90°).[34] Forearm position sense is affected by the torque as the angle becomes steeper and the error increases to 90° of flexion when the voluntary contraction is at maximum level due to gravitational forces.[34] Additionally, elbow joint torque increases as the forearm positions horizontally due to increased gravitational forces.[34] However, we only found a positive relationship between torque and matching error at 20° PARPwoVF and PARRwoVF (p<0.005). This relationship may be due to the increase in torque and demand of voluntary movement resulting from higher proprioceptive inputs.[21] Additionally, a relationship between the force of the biceps brachii muscle and the least error of

Table 6. Predictors of PARP and PARR woVF at 20° by linear regression analysis.

Task to perform	Predictors	Standardized coefficients (β)	Significance (p)
PARP	Gender (being female)	-0.49	**0.023**
	Biceps brachii strength	0.53	**0.015**
	Constant		**0.003**
PARR	Cubital angle	0.617	**0.005**
	Biceps brachii strength	0.520	**0.011**
	Constant		0.040

PARP: R=0.62; R^2=0.38, adjusted R^2=0.31. PARR: R=0.73, R^2=0.54, adjusted R^2=0.45. Bold values indicate p<0.05.

matching at 20° was found during PARRwoVF ($p<0.05$). Thus, the relationship between torque and proprioception sense at different angles should be investigated to understand their impact on the passive and resistive movements of ADL.

It was found that proprioception sense is the overwhelming factor in the transformation of the spatial information received via vision into the motions that result in muscle force and joint torques.[33] Proprioception accuracy was significantly decreased during elbow flexion at 20° and 45° when the task was performed woVF ($p<0.01$). Ultimately, these results support the effectiveness of vision on motor activity. However, according to Cruise et al., when vision is removed, visual input may have a mirror effect during the execution of elbow flexion.[36] In this case, the 'seen' position of elbow joint range is associated with its "felt" position relating to the previous history of contraction in the memory, and muscle length changes.[37] Thus, the effect of vision should be further investigated in different circumstances in future robotic studies.

Biceps brachii muscle strength played an important role in the proprioceptive sense of motion at 20º during PARRwoVF. It has previously been pointed out that the strength imbalance among trunk flexor muscles is the key factor in the lack of proprioception after fatigue in patients with chronic low back pain.[38] The cubital angle also had an effect on the proprioception sense at 20º during PARRwoVF. Female students' success was higher at 20º woVF, suggesting that gender differences in proprioception be investigated further.

Studies have demonstrated that the accumulation of fat tissue may reduce body balance and contribute towards falls among extremely obese teenage and adult patients.[39] Additionally, postural balance deteriorates with an increase in body mass as expressed by BMI.[40] However, in this study BMI was not a predictor for matching error in both groups, which may be due to the similar BMI of all participants.

Participants found the task more difficult when performed with resistance woVF. They thought that on the whole the RehabRoby as safe, easy to use and easily mounted.

The relatively small sample size can be considered a limitation of this study. Additionally, more studies should be completed at different functional angles to comparatively study the RehabRoby system for the assessment of the upper limbs.

We consider this study is a preliminary investigation of the RehabRoby as an assessment and rehabilitation tool. It can be used to diagnose and rehabilitate proprioceptive deficiencies to determine the amount of the deficiencies by comparing with the intact side and to understand matching error at the target activity.

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