Universal haptic drive: A robot for arm and wrist rehabilitation

Jakob Oblak, Imre Cikajlo, and Zlatko Matjačić

***Abstract*—In this paper we present a universal haptic drive (UHD), a device that enables rehabilitation of either arm ("ARM" mode) or wrist ("WRIST" mode) movement in two degrees of freedom. The mode of training depends on the selected mechanical configuration, which depends on locking/unlocking of a passive universal joint. Actuation of the device is accomplished by utilizing a series elastic actuation principle, which enables use of off-the-shelf mechanical and actuation components. A proportional force control scheme, needed for implementation of impedance control based movement training, was implemented. The device performance in terms of achievable lower and upper bound of viable impedance range was evaluated through adequately chosen sinusoidal movement in eight directions of a planar movement for the "ARM" mode and in eight directions of a combined wrist flexion/extension and forearm pronation/supination movement for the "WRIST" mode. Additionally, suitability of the universal haptic drive for movement training was tested in a series of training sessions conducted with a chronic stroke subject. The results have shown that reliable and repeatable performance can be achieved in both modes of operation for all tested directions.**

***Index Terms*—Haptics, neurological rehabilitation, arm, wrist, series elastic actuation**

I. Introduction

OVER the past decade, the number of people that suffered from cerebro-vascular accidents or traumatic brain injuries has substantially increased [1]. The damage to the central nervous system can lead to impaired motor control of upper and lower limbs, which represent significant difficulties in performing activities of daily living (ADL). Several studies indicated that rehabilitation based on task-oriented repetitive movements is beneficial for improvement of movement abilities [2-5].

Upper extremity function is of paramount importance to carry out various ADL. Reaching or approaching toward an object is done by shoulder and elbow, orienting of an object is accomplished by wrist, while grasping and releasing of an object is carried out by opening and closing a hand. To improve upper extremity ability after a brain lesion, an early and intensive therapy approach is needed [6]. Within the framework of motor re-learning approach and neurodevelopmental technique (NDT) [7], isolated selective movement of reaching, wrist orienting and grasping are repetitively practiced. The emphasis is on re-establishment of range-of-motion, strength, spasticity reduction and selectivity of motion. Particularly, in most of the stroke population arm reaching activity confined to a horizontal plane and wrist supination and extension movement practice are the core building blocks of neurological rehabilitation, which are needed to allow progress toward more functional whole upper extremity movement. It has been shown that intensity of the upper extremity therapy positively correlates with the motor outcome after stroke [6]. Unfortunately, the repetitive nature of therapy, which demands one-on-one manual interaction with a therapist, is time consuming as well as expensive as the majority of the healthcare budgets assigned to movement rehabilitation is related to labor costs.

There is a pressing need for a new, more cost-effective rehabilitation approaches. In order to increase the ratio between the outcome and cost of rehabilitation, robotic devices are being introduced into clinical rehabilitation [8-10]. Robot mediated rehabilitation is a rapidly advancing field. Besides the cost-effective aspect, robotic devices introduce higher accuracy and repeatability in performing rehabilitation exercises. Precise measurements of quantitative parameters by means of robotic instrumentation may improve objective monitoring of patient's recovery. Furthermore, rehabilitation robots can be combined with virtual reality environment [11, 12]. This possibility is very important, because the patient's motivation and cognitive involvement has a great impact on the outcome of rehabilitation.

The current state of the art in the field of upper extremity rehabilitation robotics includes haptic robotic solutions that have from one to three endpoint degrees of freedom and were developed for training of the shoulder and elbow: MIT-MANUS [13], GENTLE/S [14], Pneu-WREX [15], NEREBOT [16], ReoGo [17] and ARM Guide [18] as well as for wrist: CRAMER [19], RICE WRIST [20], HAND MENTOR [21], HWARD [22] and BI-MANU-TRACK [6]. The common denominator of the referenced devices is that they provide training environment for only one

Manuscript received June 10, 2009. Development of the universal haptic drive was supported by the Slovenian Research Agency and FUNDACION FATRONIK, which are gratefully acknowledged.

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component/activity of upper extremity movement; either arm reaching movement or wrist movement. Clinical studies have shown that training results are task specific; motor improvement can be expected only in the practiced aspects of movement [23]. The upgraded version of MIT-MANUS with Wrist-Robot [24], ARMIN II [25] and REHAROB [26] are rehabilitation robots that enable training of arm and wrist movement, however, these devices have up to seven active degrees-of-freedom (DOF), which necessitates complex, precise and expensive mechanisms and drives and thus may be affordable only for major rehabilitation centers. Furthermore, their use in neurological rehabilitation may take place only after the isolated components of selective movement have been adequately re-established. The penetration of the rehabilitation robotics into widespread clinical use may be significantly facilitated by lower cost hardware. Therefore, there is a need for haptic rehabilitation robots that have only few degrees of freedom, thus reducing the costs of hardware, while at the same time offering possibility of training reaching as well as wrist movement, which are essential prerequisites for rehabilitation of a more complex functional movement of upper extremity. One approach would be to conceive an innovative mechanical design of a rehabilitation robot, which would be reconfigurable in such a way that depending on the mechanical mode of operation either reaching or wrist movement would be possible.

In this paper we present the proposed concept, development of a prototype and the results of system performance evaluation of a 2 DOF haptic rehabilitation robot that enables planar reaching movement and also wrist movement as well as results of limited clinical training tests.

II. Device Description

A. Mechanism

The concept of the universal haptic drive (UHD) is presented in Fig. 1. The UHD mechanism is composed of an actuated bar inserted into a spherical joint, which is fixed to a base plate. Upon the actuated bar a series of elements are serially linked: a sliding mechanism that enables linear movement, force sensor, a passive 2 DOF universal joint that can be mechanically locked and a handle bar. If the universal joint is locked the handle bar moves according to the movement of the actuated bar, which means that inclination of 15 degrees results in horizontal change in position of 20 cm, given the selected lengths of mechanical elements (Fig. 1(a)). In this mechanical configuration, termed as "ARM" mode, a subject holding on the handle bar can perform quasi-planar reaching movement as shown in Fig. 1(b). Expression quasi-planar means that patient's hand is limited to move in the workspace with the shape of a spherical surface. The maximal vertical displacement is at the limits of the achievable workspace and is not bigger than 3 cm. If the universal joint is unlocked then the handle bar can rotate in relation to the actuated bar in 2 DOF, which means that rotation of 15 degrees of the actuated bar results in rotation of 45 degrees of the handle bar, given the selected lengths of mechanical elements (Fig. 1(a)). In this mechanical configuration, termed as "WRIST" mode, a subject holding on the handle bar and having forearm strapped to the support can perform wrist movement in 2 DOFs. The first DOF is pronation/supination of the forearm, while the second DOF depends on the orientation of the handle bar. When the handle bar is oriented horizontally, wrist flexion/extension movement can be performed, while in the vertical orientation ulnar/radial deviation movement can be performed as shown in Fig. 1(c). Achievable ROM of UHD in "WRIST" mode and human wrist ROM [24] are presented in Table I. It is important to point out that in "WRIST" mode a length difference ΔD (Fig. 1(a)) of the mechanism below the universal joint occurs, which is due to fixed forearm support and is compensated with movement of the sliding mechanism.

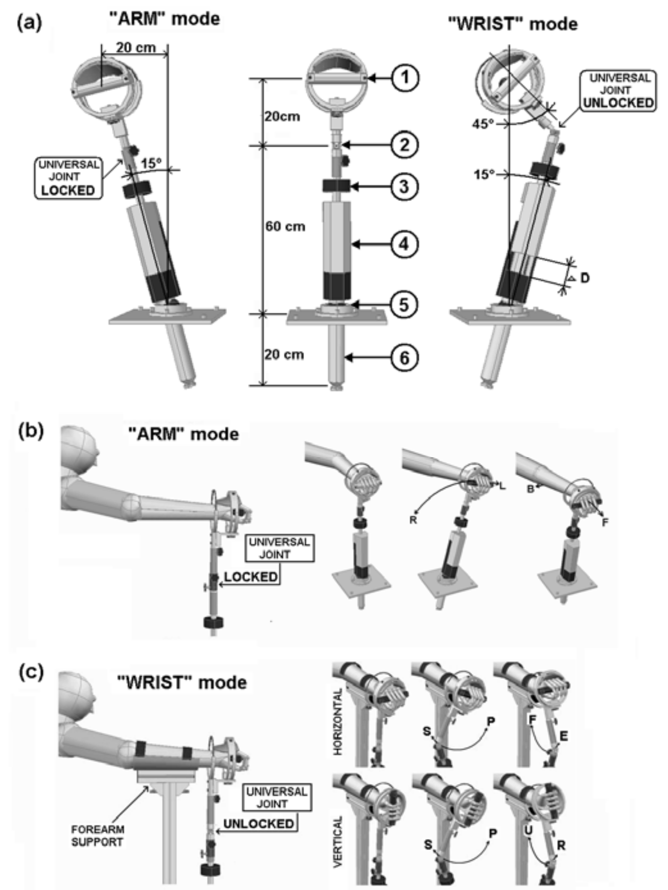

Fig. 1. (a) Universal haptic drive (UHD) is composed of: 1-handle bar, 2-universal joint, 3-force sensor, 4-sliding mechanism, 5-spherical joint and 6-actuated bar. Switching between "ARM" and "WRIST" mode can be easily achieved by locking or unlocking universal joint on the actuated bar. In "WRIST" mode, the length difference ΔD of the bar under the universal joint is compensated with sliding mechanism. (b) In "ARM" mode universal joint is locked. Movement in R-ight, L-eft, B-ackward and F-orward directions is possible. (c) In "WRIST" mode universal joint is unlocked and forearm is supported to fix the centre of wrist joint. When handle bar is set in HORIZONTAL position, S-upination/P-ronation and F-lexion/E-tension can be exercised. Setting the handle bar in VERTICAL position enables to exercise S-upination/P-ronation and U-lnar/R-radial deviation.

TABLE I
ROM IN HUMAN WRIST AND UHD

	Range Of Motion (ROM)	
	WRIST	**UHD**
SUPINATION	70°	45°+ OFFSET
PRONATION	70°	45°- OFFSET
ULNAR	45°	45°
RADIAL	30°	45°
FLEXION	60°	45°
EXTENSION	60°	45°

By setting appropriate OFFSET angle of the handle bar from -45° to +45°, UHD's pronation/supination ROM can be changed from 0° to 90°. However, by increasing supination's ROM, pronation's ROM is reduced and vice versa.

B. Actuation

The actuation of the UHD is presented in Fig. 2. It consists of two sets of DC motors with gears and encoders, which are connected in series with elastic springs to the actuated bar by means of string wires and pulleys as shown in Fig. 2(a,b). Both motors actuate movement of the actuated bar in the perpendicular directions A and B. The maximal continuous torque of the selected DC motors (Maxon, RE 40, 150 W) with Maxon Planetary Gearhead (GP 52 C, 81:1) is approximately 15 Nm. The radius of the pulley attached to the gearhead is 5 cm, which means that the maximal force that can be exerted on the actuated bar in linear direction is 300 N (15 Nm / 0.05 m). Therefore, the maximal continuous force that can be applied on the handle bar in "ARM" mode is 75 N (300 N * 1/4) and the maximal continuous torque provided in "WRIST" mode is 20 Nm (300 N * 1/3 * 0.2 m).

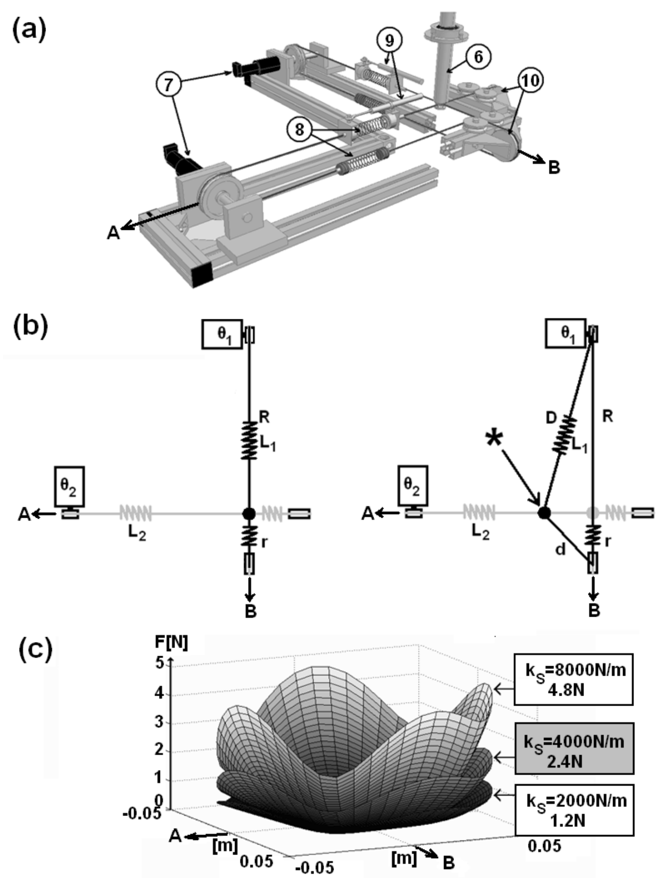

Fig. 2. (a) Actuation of UHD consists of: 7-DC motors, 8-elastic springs, 9-linear potentiometers, 10-pulleys and 6-actuated bar. Motors, springs and actuated bar are connected with string wires. (b) By moving actuated bar in horizontal direction A (*), the geometry of the actuation in vertical direction B changes from R + r to D + d. (c) Resistive force, which appears due to geometrical design of the UHD actuation, is calculated for three different spring stiffness values over the whole range of motion of the UHD.

There are two reasons for utilization of series elastic elements in the actuation. The first reason is related to the geometrical design of the UHD actuation. The distance as measured from the shaft of the motor to the pulley located on the opposite side of the actuated bar is affected by the movement of the actuated bar in the perpendicular direction as depicted in Fig. 2(b) (D + d ≠ R + r). The change in the lengths of both springs of the actuation system in B direction generates a force that acts on the actuated bar in A direction and tends to move the actuated bar back in "zero position". The magnitude of this coupling force depends on the position of the actuated bar as well as the stiffness of used springs. This dependence is illustrated in Fig. 2(c) for three different spring stiffness values. One can observe that the greatest coupling between the A and B directions of movement takes place at the limits of the achievable workspace of the actuated bar. However, this coupling is rather weak and does not represent an important factor in the design of the actuation system.

The second reason to use springs relates to the effect that, by introducing an elastic element in series with the motor we have actually designed a Series Elastic Actuator (SEA), which provides many benefits in force control. These benefits include greater shock tolerance, lower reflected inertia, more accurate and stable force control and the capacity for energy storage [27-30]. However, these benefits come with one shortcoming, which is related to reduction of the achievable bandwidth. This is illustrated by a simple linear model for an actuator with a series elastic element, where all parameters and variables are converted from rotational to translational motion as shown in Fig. 3(a).

Dynamics of the system, where the load is assumed to be clamped, is determined by the following two equations:

$$2 * k_S (X_M - X_L) = F_L \qquad (1),$$

$$F_L + F_M = m_M \ddot{X}_M + b_M \dot{X} \qquad (2),$$

where F_M is the motor's force converted from the motor torque; $2*k_S$ is the double stiffness of the spring, (see Fig. 3(a)) while x_L and x_M are the positions of the load and motor. Values m_M (36,7 kg) and b_M stand for reflected motor mass and reflected viscous friction in motor and planetary gearhead. By taking Laplace transforms and assuming that the output of the actuator is clamped ($x_L = 0$), the transfer function between the output force F_L and the motor force F_M is given by:

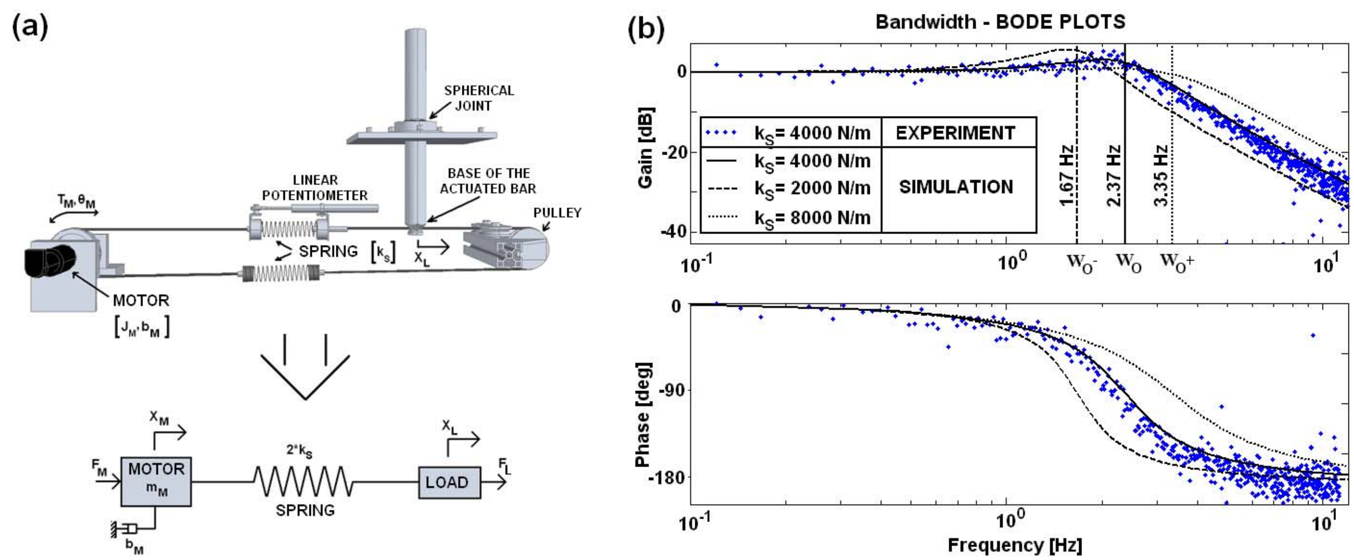

Fig. 3. (a) Model of the actuator, where all parameters and variables are converted from rotational to translational motion. (b) Bode plots of open-loop dynamics of a series elastic actuator with fixed load. Shown are experimental results as well as simulation results for three different values of spring stiffness.

$$G(s) = \frac{F_L(s)}{F_M(s)} = \frac{1}{1 + s\dfrac{b_M}{2 * k_S} + s^2\dfrac{m_M}{2 * k_S}} \quad (3).$$

The equation (3) presents open-loop dynamics of a series elastic actuator with fixed load. Fig. 3(b) shows the Bode plots of equation (3), for three different values of stiffness of the springs. One can observe good agreement between the input motor force F_M and output load force F_L for frequencies below the natural frequency w_O, which depends on the spring stiffness:

$$w_O = \sqrt{\frac{2 * k_S}{m_M}} \quad (4).$$

In general, the stiffer the spring the larger bandwidth of the actuation system can be achieved.

Since the UHD device is predominantly intended for rehabilitation purposes where relatively slow movement can be expected during training we have experimentally determined that the spring stiffness value of k_S = 4000 N/m provides sufficient actuator bandwidth on one hand while on the other hand provides also sufficient attenuation of backlash and friction nonlinear effects as well as actuator's own impedance.

Open-loop dynamics of SEA with fixed load used in the UHD was assessed in experimental measurements. The experiment was done by fixing the load of the actuator and sweeping the frequency spectrum of the actuator input. The damping term (b_M = 400 Ns/m) was determined experimentally by fitting model damping term to match simulation results with experimental measurements, see Fig. 3(b).

C. Control

Haptic devices used in rehabilitation are typically controlled in such a way to: i) provide unhindered movement, i.e. the interaction force between the haptic device and the hand of the user should be as small as possible to give a feeling of »an empty space«; ii) provide a force »tunnel« along the desired movement trajectory where radial force typically proportionally increases with the radial deviations from the desired trajectory, thus forcing the hand of the user back to the desired trajectory while force tangential to the desired trajectory also proportionally increases if the user is either lagging or leading the desired trajectory in the tangential direction. Haptic devices can be also used for offering continuous partial assistance or partial resistance to the patient along the desired trajectory.

Fig. 4(a) shows the photograph of the actual prototype of the UHD device configured to enable movement training in »WRIST« mode, while Fig. 4(b) shows schematic diagram of the implemented impedance based force control of UHD. A conventional proportional force control scheme, which is needed for implementation of impedance control based movement training, was implemented independently in each actuated DOF. Because the coupling between both actuated DOF's that appears due to actuation design is relatively weak, no compensation of this coupling was implemented in the control scheme. The values of the controller gain were the same for both DOFs and were determined experimentally. The force feedback signal was measured by means of JR3 (JR3, Woodland, USA) force sensor, which was mounted on the actuated bar (Fig. 1(a)). The desired force was calculated from selected impedance parameters and kinematics of the actuated bar. The position of the actuated bar was determined by the positions of the encoders (θ_1, θ_2), mounted onto DC motors, and the lengths of the springs (L_1, L_2), which were measured with linear potentiometers (Fig. 2(a,b)). The control scheme

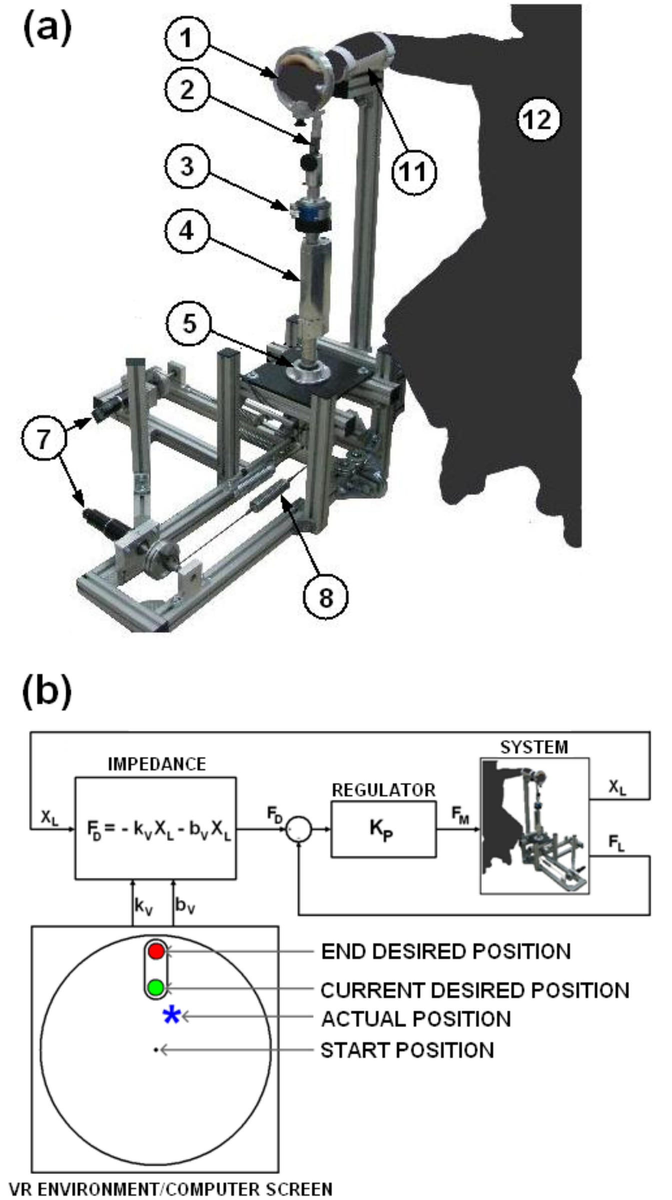

Fig. 4. (a) A photograph of the UHD prototype: 1-handle bar, 2-universal joint, 3-force sensor, 4-sliding mechanism, 5-spherical joint, 7- DC motors with gears and encoders, 8-elastic springs, 11-forearm support ("WRIST" mode) and 12-user. (b) Schematic diagram of impedance based force control of UHD.

was implemented in Simulink (MATLAB) and run in real time on xPC target platform with the sampling frequency of 1 KHz. All the signals from the sensors were assessed with National Instruments 6025 Data Acquisition Card (National Instruments, Texas, USA).

III. Experimental Evaluation - System Performance

The principle function of the UHD is to ensure a haptic interface between a user and a computer simulation based training task. Therefore, the device performance can be estimated by measuring how precisely the UHD can exert required force on a user. Because impedance control strategy was used, the required force we want to exert on the user's hand was set by a selection of the virtual impedance of the UHD. Virtual impedance is typically bounded with the lowest achievable impedance, which would ideally be zero, and the highest achievable impedance, which would ideally be infinite. Therefore, the quality of a haptic interface can be determined by examining the performance in "LOW IMPEDANCE" and "HIGH IMPEDANCE" environment. In "LOW IMPEDANCE" environment the objective is "zero" force control, meaning that the interaction between a user and the UHD should be minimal while moving in the UHD workspace. That situation is typical for user-in-charge oriented exercises. Opposite situation occurs, when we want the UHD to generate the biggest possible resistive force. That situation is common for robot-in-charge mode or when we want to simulate "HIGH IMPEDANCE" environment. However, conservative requirement for stability of SEA actuators (in terms of passivity of a human-machine interface) is that maximal virtual stiffness is limited by the intrinsic mechanical spring stiffness [30], which is in our case 4000 N/m. Since, the actuated bar is fixed between two pre-tensioned springs, Fig 3(a), the overall stiffness equals 8000 N/m. Ratio of force that is transmitted from the bottom of the actuated bar to the handle bar is 1:4; see Fig. 1(a). Similar ratio for movements is 4:1. For this reason, the maximal stably achievable stiffness at the handle bar is 16 times smaller than on the bottom of the actuated bar. In the "ARM" mode this value equals approximately to 500 N/m. Similar consideration for "WRIST" mode yields stiffness of 20 Nm/rad.

The UHD performance was verified for both "LOW IMPEDANCE" and "HIGH IMPEDANCE" environment. Because the UHD allows performing exercises in "ARM" and "WRIST" modes, we measured forces/torques for both modes. In the conducted experiment we also measured the UHD's own impedance, by switching the motors off and monitoring the forces/torques. The UHD performance was examined in experimental trials involving one healthy subject. Fig. 5(a) shows single repetitions denoting the full range of motion and directions of movement for both modes. The experimental evaluation was carried out by moving ("ARM" mode)/rotating ("WRIST" mode) the handlebar in a given direction for approximately ±8 cm/ ±30° with a frequency of approximately 1 Hz while simultaneously measuring the force interaction between the user and the UHD device. This frequency was selected as being close to the upper bound of expected frequency range in upper limb movement rehabilitation. As can be seen from the Fig. 5(b), showing the performance of the UHD in "ARM" mode, the maximal force that the user felt in "LOW IMPEDANCE" environment was approximately 2.5 N, which is much smaller than in the case when the motors were switched off, where the maximal force was approximately 10 N. On the other hand, forces that appear in "HIGH IMPEDANCE" environment were approximately 40 N, which corresponds well to a desired virtual stiffness of 500 N/m. Fig. 5(c) shows performance of the UHD in "WRIST" mode where the maximal torque that the user felt in "LOW

TABLE II
DEVICE PERFORMANCE TESTED IN EIGHT DIFFERENT DIRECTIONS FOR BOTH MODES OF OPERATION

	“ARM” mode: force[N] (mean ± standard deviation)			**“WRIST” mode:** torque[Nm] (mean ± standard deviation)		
DIRECTION See Fig. 5 (a)	*“LOW IMPEDANCE”*	*“HIGH IMPEDANCE”*	*“ACTUATION OFF”*	*“LOW IMPEDANCE”*	*“HIGH IMPEDANCE”*	*“ACTUATION OFF”*
1	2.46 ± 0.17	39.90 ± 1.38	8.91 ± 0.47	0.62 ± 0.02	7.01 ± 0.04	1.81 ± 0.11
2	2.66 ± 0.11	36.48 ± 1.64	8.64 ± 0.33	0.75 ± 0.03	7.20 ± 0.35	1.82 ± 0.05
3	2.48 ± 0.15	38.48 ± 2.17	8.69 ± 0.57	0.72 ± 0.05	6.33 ± 0.13	1.31 ± 0.04
4	2.58 ± 0.13	39.94 ± 0.67	10.10 ± 0.27	0.77 ± 0.06	6.16 ± 0.26	1.49 ± 0.04
5	2.30 ±0.21	37.78 ± 2.09	8.42 ± 0.55	0.70 ± 0.05	6.68 ± 0.14	1.41 ± 0.11
6	2.80 ± 0.19	36.02 ± 253	8.81 ±0.21	0.78 ± 0.04	6.97 ± 0.33	1.85 ± 0.08
7	2.46 ±0.34	41.20 ±1.82	8.93 ± 0.46	0.68 ± 0.05	6.78 ± 0.19	1.93 ± 0.05
8	2.69 ± 0.15	42.04 ±1.98	9.10 ± 0.15	0.71 ± 0.04	7.94 ± 0.23	2.11 ± 0.12

The amplitude of movement was approximately ±8 cm / ±30°; the frequency of movement was approximately 1 Hz.

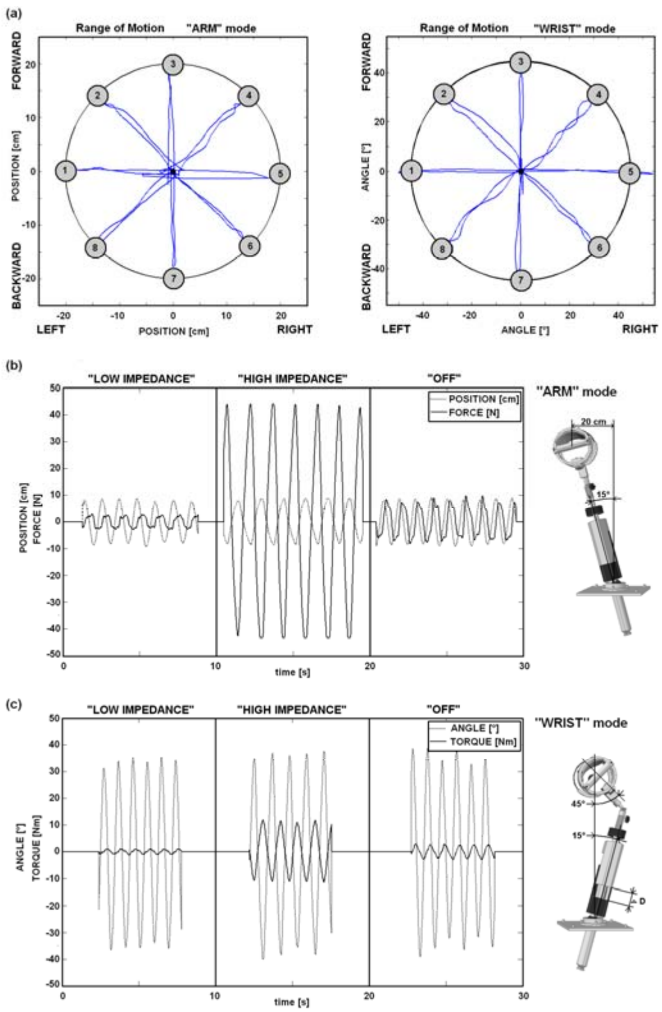

Fig. 5. (a) Ranges and directions of motion for “ARM” and “WRIST” modes. (b) Device performance in “ARM” mode. Plot shows the force (solid line) that user can feel on the handle bar, while making similar movements in forward/backward direction (dotted line). In the first 10 seconds UHD performed “LOW IMPEDANCE” environment. In time interval from 10 to 20 seconds “HIGH IMPEDANCE” environment was performed and in the last 10 seconds, the motors were switched off. (c) Device performance in “WRIST” mode. Plot shows the torque (solid line) that a user can feel on the handle bar, while making similar supination/pronation movements (dotted line). In first 10 seconds UHD performed “LOW IMPEDANCE” environment. In the time interval from 10 to 20 seconds “HIGH IMPEDANCE” environment was performed and in the last 10 seconds, the actuation was switched off.

IMPEDANCE” environment was approximately 0.7 Nm, which is much smaller than in the case when the motors were switched off, where the maximal torque was approximately 1.8 Nm. On the other hand, torques that appear in “HIGH IMPEDANCE” environment were approximately 7 Nm, which corresponds to a virtual stiffness of 20 Nm/rad.

Table II shows the results (mean values and standard deviations) for different impedance modes for five repetitions of movement in each of the eight tested directions for “ARM” and “WRIST” mode. The qualitative inspection of the results in various directions shows that the performance of the UHD is similar in all tested directions for different modes of operation. Quantitative analysis of these results would not be appropriate, since the movement, performed by the tested subject, was rather variable.

IV. EXPERIMENTAL EVALUATION – CLINICAL TESTS

The developed UHD device was tested also in a series of training sessions in which movement of arm and wrist was practiced by a volunteer subject (10 years post stroke), with chronic, right-sided hemiparesis resulting in limited movement abilities in shoulder, elbow and wrist as well as grasp (score 5 out of 7 on Utrecht Arm/Hand Test). The subject gave informed consent for the experimental tests, which were approved by the Slovenian national ethics committee. The primary objective of these clinical tests was to determine whether the achievable impedance range of the UHD device, presented in the previous section, is suitable for adequate assistance in movement tracking tasks.

Overall six training sessions were performed on six consecutive days in both “ARM” and “WRIST” modes of operation. The training protocol for each session consisted from performing tracking movement, first of the wrist and followed by the arm. The duration of each training session was approximately 45 minutes. Training of the movement was in form of tracking tasks, which were for the wrist confined consecutively, only to each single degree of freedom: ulnar/radial deviation, pronation/supination and flexion/extension while training of the arm movement included tracking tasks in eight directions within the plane of movement. Range of motion in tracking tasks was determined such that the subject was comfortable with the extent of movement. Tracking trajectories were composed by using polynomial functions with time as independent variable

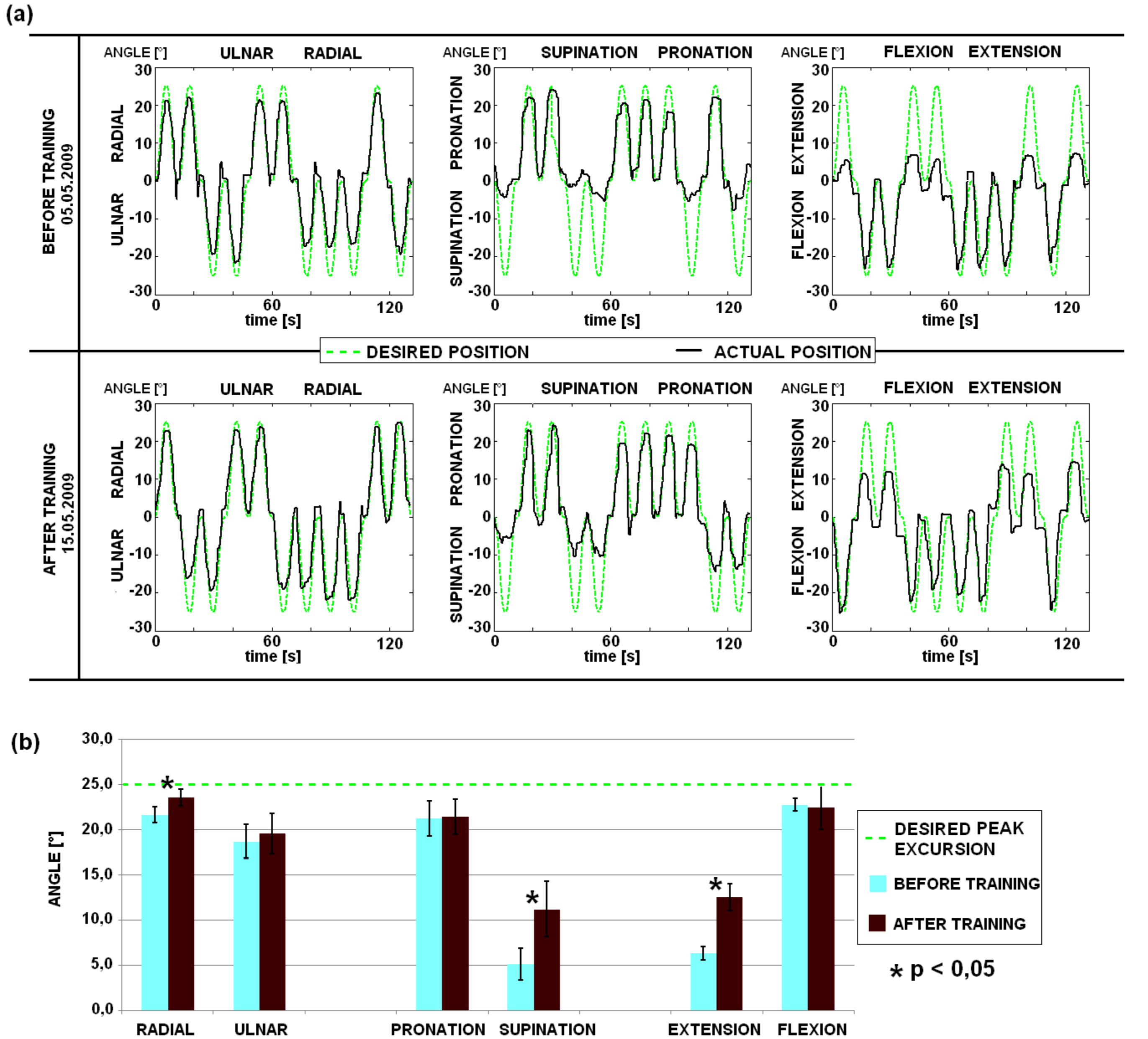

Fig. 6. (a) Subject's tracking performance in "WRIST" mode before (dotted lines) and after (solid lines) the training. (b) Ranges of motion before and after the training.

similarly as described in [10]. Impedance controller assistance implemented during the movement tracking tasks was also similar to the one described in [10] where the UHD device opposed to deviations in radial directions in accordance to selected impedance parameters (virtual stiffness and damping, Fig. 4(b)), while in the tangential direction the subject was assisted if she lagged behind the required reference trajectory with the force/torque proportional to the selected parameters of impedance controller. The desired position and actual position were displayed on computer screen in a form of easily visible circular objects, Fig 4. (b); therefore the training tasks were visually cued. If the subject's movement was faster than the movement of reference trajectory the UHD provided no assistance. Throughout the training sessions the impedance parameters were gradually decreased, according to the gradual progress in patient's progress in the following ranges: virtual stiffness k_V = 500–200 N/m ("ARM" mode); 20–8 Nm/rad ("WRIST" mode) and virtual damping b_V = 8–4 Ns/m ("ARM" mode); 0.5–0.25 Nms/rad ("WRIST" mode). Training of each movement modality (3 wrist movements and planar arm movement in 8 directions) consisted of seven minutes activity. In the first two minutes of tracking the subject was instructed to be passive while the impedance controlled UHD device performed tracking of the reference trajectories. In the following five minutes the subject was instructed to follow or if possible to be ahead of the reference trajectory while the UHD provided assistance according to the characteristics of the impedance controller as described above.

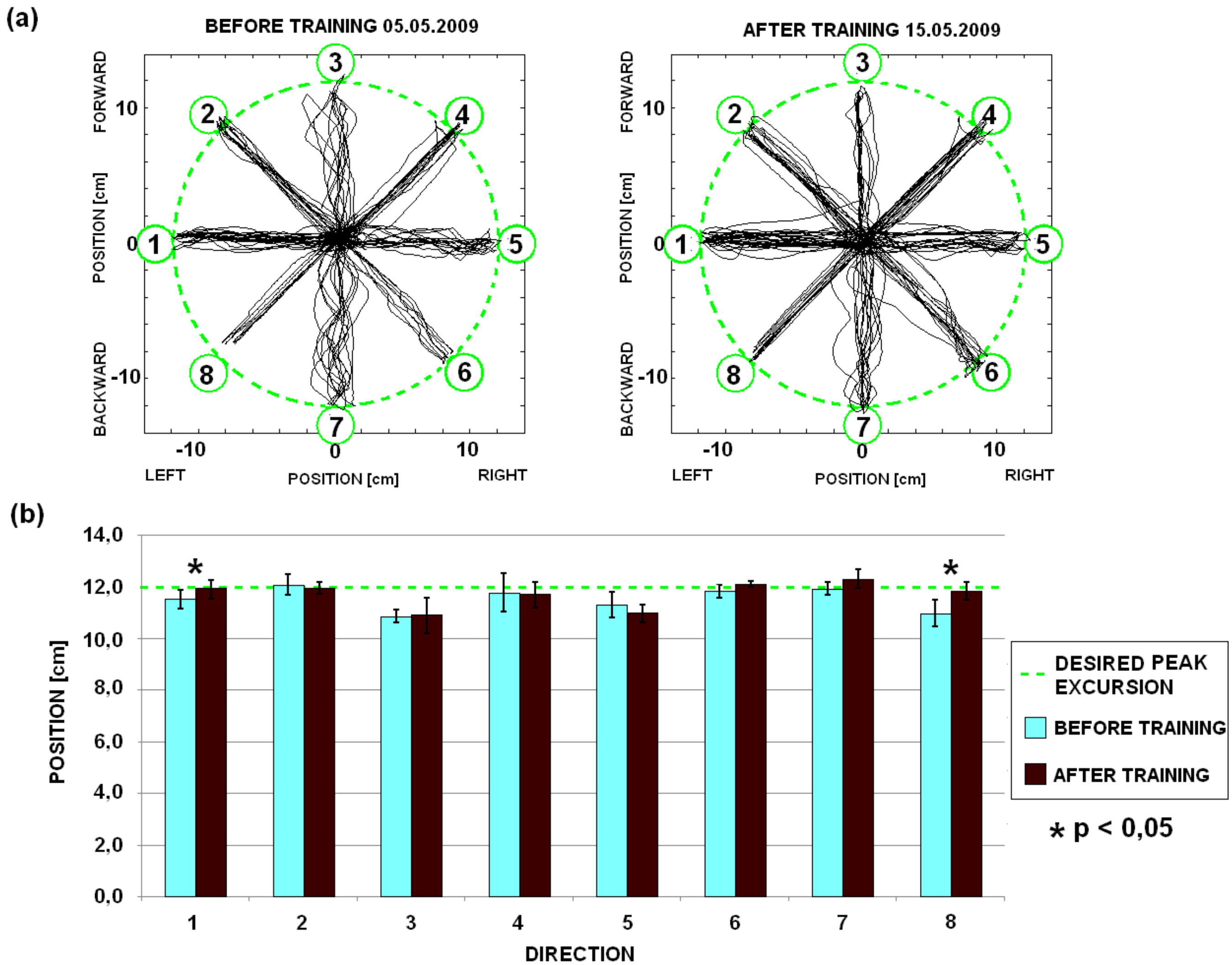

Fig. 7. (a) Subject's tracking performance in "ARM" mode before and after the training. (b) Ranges of motion in each of the tracking directions before and after the training.

On the first day and the last day of the training period the tracking performance of the subject was evaluated in conditions where the impedance controller provided no assistance but was set-up to maintain "LOW IMPEDANCE" environment in radial as well as tangential directions relative to reference tracking trajectory directions. The range of motion for each trained degree of freedom (for wrist radial/ulnar deviation, pronation/supination and flexion/extension; for arm eight directions in the plane of movement) was determined as the mean peak value of five repetitions. Range of motions before and after the six training sessions was compared in paired t-test. Level of statistical significance was set to $p<0.05$.

Fig. 6 shows the tracking performance for each degree of freedom of the wrist before and after the training. One can observe that in neither direction the subject was able to reach the required peak excursions (set to ±25°). The most difficulties in movement the subject experienced in the forearm supination and wrist extension, which was markedly improved after the training.

Fig. 7 shows the tracking performance for planar arm movement before and after the training. The results show that the subject could perform the required task satisfactorily already before the training. The performance after the training was similar where modest improvement can be observed in two of the eight tracking directions. Also, after the training one can observe improved coordination of movement in the directions 3 and 7.

V. Discussion

This paper presented the universal haptic drive, a device that can be used for arm as well as wrist rehabilitation. The UHD is designed in a way that allows performing exercises in two different modes, "ARM" mode and "WRIST" mode, which enable movement in two degrees of freedom, depending only on the mechanical configuration of the device, while exactly the same controller and the same controller's gains are used for both modes of operation.

Results show that entirely acceptable performance can be expected in both modes of operation. The frequency and amplitude of movement selected for experimental evaluation of UHD performance (Fig. 5) was rather high and can be regarded to represent the upper limit of practiced movement in rehabilitation. The maximal force that the user feels in low impedance environment termed as "an empty space" was similar to performance of other "single-task" haptic devices, for example MIT wrist robot [24].

SEA-based actuation system utilized in the UHD device successfully enabled generation of LOW IMPEDANCE environment in both modes of operation. Generation of HIGH IMPEDANCE environment is limited to a stiffness of 500 N/m for the "ARM" mode and 20 Nm/rad for the "WRIST" mode, which is due to a conservative requirement for stability of SEA actuators [30]. However, this should not represent a notable limitation in rehabilitation where more compliant and thus gentle guiding in performing a task under training is necessary as recent clinical results [9] suggest that such an environment is much more stimulating for re-learning of movement as compared to a rather rigid implementation of a stiff virtual wall. Also the clinical training tests that were performed with the post-stroke subject have shown that the achievable impedance range of UHD is sufficient to: i) guide the movement of the subject's arm/wrist also in conditions where no effort is provided on the part of the user and ii) bring about the training results similar to other "single-task" devices [2, 5].

It is common understanding that today's haptic devices used in rehabilitation are too expensive, which represents the major impediment for their widespread use. The cost of robotic devices for rehabilitation could be reduced by i) using standard mechanical components that are produced in large quantities and ii) by designing mechanisms to enable training of various aspects of upper extremity movement. The proposed haptic device presented in this paper is made from off-the-shelf mechanical components, motors and motor drives. Also low cost single DOF force load cells or even measurements of springs elongations could be used in the future instead of multi-axis robotic wrist force sensor.

The developed universal haptic drive offers similar quality of a haptic training environment for practicing movement of the arm and the wrist, where the mode of training depends only on the configuration of mechanical linkage.

The UHD device presented in this paper has potentially two major advantages over single-purpose (either reaching movement or wrist movement) rehabilitation robots [6, 13-22]: i) it enables isolated training of specific movement of arm and wrist and ii) by combining mechanical structure with SEA-based actuators the cost of hardware may be significantly reduced thus possibly enabling future development of rehabilitation robots for home use. Through presented innovative approach haptic training environment may become more readily available to a major portion of stroke population that is in need of a targeted, specific movement training of both arm and wrist movement. Such targeted, specific movement training must precede attempts of whole upper extremity functional movement training that can be facilitated either by a human therapist or an exoskeleton type of rehabilitation robots with many degrees of freedom [25]. In the current design of the UHD only reaching movement in the horizontal plane is possible. However, one can easily imagine that if the handle was displaced by a firm rod for example laterally from the force sensor, in the direction parallel to the users' arm, then the reaching movement in the forward direction would incorporate also a component of vertical movement. In further development of UHD device we will focus on improvements of a mechanism that will enable practicing reaching in needed directions for each individual user.

In this paper we have demonstrated that rather simple mechanisms, which enable training of various aspects of upper extremity movement by employing limited number of actuated DOFs, can be successfully designed and implemented for purposes of neurological rehabilitation.

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