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Preliminary Mechanical Design of NU-Wrist: a 3-DOF Self-Aligning Wrist Rehabilitation Robot

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Abstract— **The use of robotics in rehabilitation area provides a quantifying outcomes on treatment of after stroke patients. This paper presents the preliminary design of a novel exoskeleton robot, called NU-Wrist, for human wrist and forearm rehabilitation. The proposed robot design provides rotation within the anatomical range of human wrist and forearm motions. A novel compliant robot handle link ensures dynamic passive self-alignment of human-robot axes during therapy exercising. The proof-of-concept wrist robot prototype has been manufactured using 3D printing technology for experimental design evaluation. It is shown the proposed NU-Wrist robot design is satisfied to the specified rehabilitation system requirements.**

I. Introduction

Approximately 15 million people worldwide suffer from cerebrovascular accidents or stroke each year [1]. According to statistics, annually 473 people out of 100,000 experience cerebrovascular accidents in Kazakhstan alone [2]. This number is more than twice higher than in the United States, where 183 out of 100,000 people reported to have stroke each year [3]. The stroke is one of the major factors leading to decreased motor function of the human upper limbs. Such patients are significantly restricted in their daily social and household activities. It is widely recognized that an appropriate post traumatic care and rehabilitation therapy is needed for recovering patient's lost abilities and their returning to normal daily activities [4]–[6]. Normally, this is achieved through long-term intensive and repetitive rehabilitation therapy regime. Conventional rehabilitation therapies are effort intensive and require manual assistance of physiotherapists to patients during exercise, leading to therapist exhaustion [7], [8]. Another issue is that conventional rehabilitation methods lack quantitative performance feedback. So, it is hard to assess the ability to move the upper limb without corresponding data support. This factors stimulate introduction of alternative rehabilitation approaches.

Robot-aided therapy is an emerging part of post-stroke rehabilitation care [9]. Rehabilitation robotic systems provide intensive motor therapy, which can be performed in a repetitive, accurate and controllable manner [10], [11]. Moreover, the therapeutic action of the robot can be adjusted to the patients motor abilities [12], [13]. Robotic devices may offer the required amount of motor practice and reduce the effort of therapists performing the rehabilitation procedure [14], [15]. In addition, the demonstrative performance assessment of patients during the therapy can be easily implemented and evaluated by therapists to make more accurate decisions on proceeding with the treatment [16], [17]. Rehabilitation robots can be also equipped with a virtual environment to provide entertaining and motivating background for patients, which can lead to incrementing of the exercise intensity [18].

There is a wide range of robotic systems have been developed for upper limb rehabilitation. Examples of the systems designed to assist upper limb proximal joint rehabilitation, i.e. shoulder and elbow, include LIMPACT [1], MIT-Manus [19], MIME [20]. Wrist and forearm rehabilitation robotic systems are mainly designed as one to three end point DOFs devices. CR2-Haptic [21] has only one rotational DOF. However, this system can be manually reconfigured to treat any specific wrist movement one at a time. Universal Haptic Drive [22], Bi-Manu-Track [23] and Supinator Extender [24] systems provide 2-DOF rehabilitation. A few 3-DOF robot systems such as RiceWrist [25] and CRAMER [26] utilize parallel mechanisms for wrist and forearm rehabilitation.

To allow the closest alignment of a rehabilitation robot joints with the anatomical wrist center of a patient hand, the 3-DOF series kinematic configuration with three revolute joints is employed in several wrist rehabilitation robot designs with each revolute joint being responsible for one DOF. Such exoskeleton type systems allow independent control of specific movements of the wrist, thus enhancing functionality of the robotic device from rehabilitation point of view. 3-DOF RiceWrist-S [27] haptic exoskeleton system, which is the next evolution of RiceWrist [25], has been redesigned as a series haptic exoskeleton mechanism. The system employs a passive linear DOF on the handle in order to keep the user's wrist in an anatomically natural posture. 3-DOF WristGimbal [28] three axis gimbal design can adjust the center of rotation of the axes to match the anatomical wrist center. A 3-DOF self-aligning wrist exoskeleton presented in [29] implements dynamic self-alignment to compensate for misalignment for the human wrist and forearm. The self-alignment is achieved by using parallelogram linkages.

Ideally, the robot-assisted therapy should be accessible to everyone through special services in hospitals or independent training in home conditions. However, currently most of the rehabilitation robotic systems are very expensive and are affordable only for use in specialized rehabilitation centers in limited quantities. This is especially visible in developing countries that do not produce such systems themselves. Often, upper limb rehabilitation systems remain for a long

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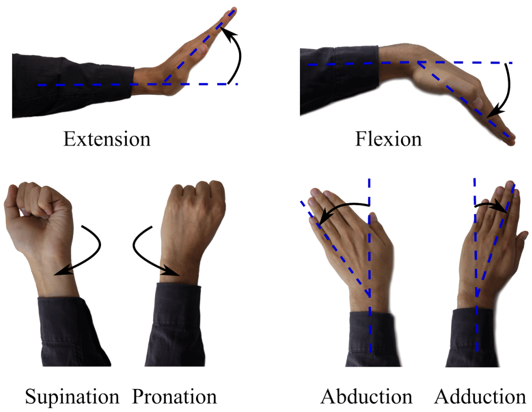

Fig. 1. Human wrist degrees of freedom

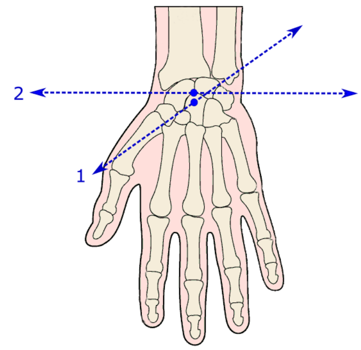

Fig. 2. Two motion axes in a human wrist joint: 1 - anteroposterior axis for abduction/adduction, 2 - transverse axis for flexion/extension

time at a clinical research stage and are available only to a limited number of volunteer patients in selected research centers, mostly located in developed countries conducting research in this field. Presently, the rehabilitation robotic devices' niche in Kazakhstan is free due to the absence of local research groups and manufacturers. The statistics stated above demonstrates a significant demand in such rehabilitation robotic systems in the Central Asia region.

In this paper, the authors present their initial results on establishing rehabilitation system research in Kazakhstan. In particular, a novel self-aligning 3-DOF robotic system for wrist and forearm rehabilitation, called NU-Wrist, is proposed. The presented wrist robot design allows passive adaptation for misalignment in wrist joint, thereby allowing to decrease user-robot interaction forces. The structure of the paper is organized as follows: Section II outlines the specified robot design requirements. Section III presents the proposed mechanical design of NU-Wrist robot whereas the results and conclusions are presented in Section IV.

II. Wrist Rehabilitation System Requirements

A. Wrist Motion Analysis

In order to develop ergonomically sound design a rehabilitation robotic system must conform to natural movements and limitations of a human wrist. The human wrist in combination with the forearm adds up to 3 DOFs. The forearm is capable of pronation and supination, and wrist is capable of flexion and extension, abduction (radial deviation) and adduction (ulnar deviation) movements as shown in Fig. 1. The typical ranges of motion for pronation/supination vary from 85° to 90° respectively. The magnitude of radial deviation is only 15°, while ulnar deviation reaches the amplitude up to 45°, when the wrist is being held in the neutral location between flexion/extension. In its turn, flexion/extension motions have a range of up to 85°, with the wrist in the neutral position between abduction/adduction [30]. The required motor-torques vary from 2 to 4 Nm and are based on the torque requirements for active daily life activities [29].

A wrist joint has two rows of carpal bones that allow motion in two axes in the joint: radial/ulnar deviation along the anteroposterior axis and flexion/extension along the transverse axis as illustrated in Fig. 2 [30]. There is an eccentricity between the rotational axes of abduction/adduction and flexion/extension groups: the axes distally deviate aside by 5 mm to 20 mm [31]–[33]. Moreover, due to complex wrist bone structure, the axes of rotation are not fixed [34]. Thus, without correct axis alignment the rehabilitation system become uncomfortable and potentially unsafe in use [1], [35]. However, manual axes alignment is a challenging task in practice that often increases time of training sessions. Therefore, the self-alignment of the human-robot axes is desirable.

B. System Design Objectives

A rehabilitation robot design follows the specified requirements regarding the DOFs, range of motion, size, mechanism type. Ideally, the robot should promote full anatomical range of motions and corresponding kinematic compatibility. Robot needs to be well balanced to replicate natural hand movement, adjustable to user, thus, possess specific sizing and be able to accommodate complex nature of human wrist joints.

One of most critical issue in the exoskeleton design is the human-robot axes misalignment [35], [36]. Complex human upper limb musculoskeletal system and individual anatomical dimensions affect human-robot axes alignment in a robotic system. Therefore, the rehabilitation robot should minimize dynamic misalignments and prevent abnormal movement patterns. Besides, to ensure safe and comfortable operation over a long duration of time, it should be minimally obstructive [37], [38]. Exoskeleton based systems should have lightweight structure as it is desirable to make the robotic system transportable. For safety reasons, the robot must have software and hardware based safety protection in the form of mechanical limits and an emergency stop button.

It is shown in [39] that additive manufacturing techniques offer visible benefits for quick prototyping, geometric design freedom, small-scale fabrication, and low-density material options in designing rehabilitation exoskeleton systems. Therefore, 3D printing technology can be utilized for initial prototype development as they allow fast progression of the

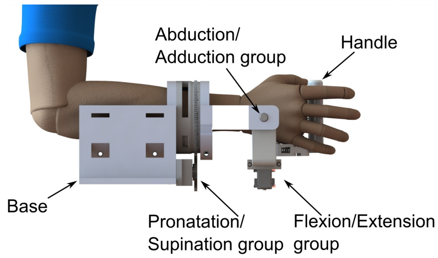

Fig. 3. Rendered side view of NU-Wrist robot with a human arm CAD model. The device can either be installed on a table or worn by user

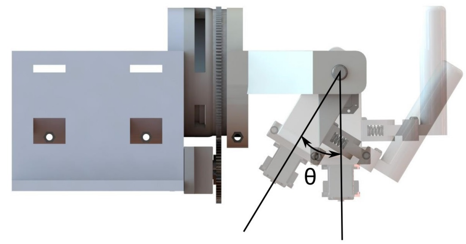

Fig. 5. Side view of the NU-Wrist robot demonstrating radial/ulnar deviation motion

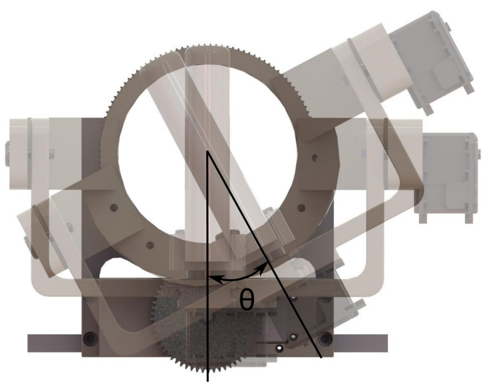

Fig. 4. Front view of NU-Wrist robot demonstrating pronation/supination motion

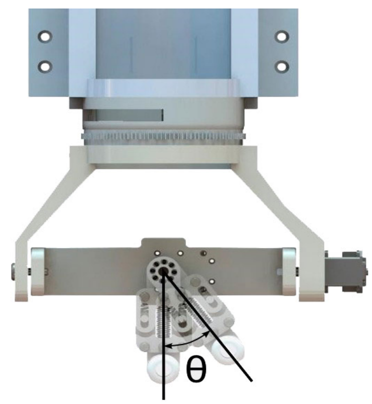

Fig. 6. Top view of the NU-Wrist robot demonstrating flexion/extension motion

design process as well as cost and time effective means to fabricate small quantities of custom prototypes [40].

The most popular type of actuation is electric actuation. Electric motors are widespread devices having different sizes, and torque capabilities, thus they perfectly suit most of the robotic applications, including robot-assisted wrist rehabilitation systems. Electrically actuated systems are easier to control comparing to pneumatic ones. Moreover, electric actuators ensure sufficiently high power-to-weight ratio. The main issue that needs to be properly addressed is the high impedance of electric motors that can be potentially harmful to patients. This can be easily overcome by implementing advanced impedance control algorithms and/or introducing elastic transmission elements between the mechanical joints and actuators.

III. Wrist Rehabilitation Robot Design

A. Robot Design

Following the specification of the design objectives in Section II, the proposed NU-Wrist robot for wrist and forearm rehabilitation is designed as an exoskeleton mechanism that can be located stationary on a table or worn by user. The NU-wrist consists of three revolute joints at the wrist part which correspond to wrist supination/pronation, flexion/extension and radial/ulnar deviation motions. The prototype design is done in the SolidWorks 3D CAD software as shown in Fig. 3 that allows direct prototyping with 3-D printing technology. The designed robot structure implements mechanical limits preventing the robot joint motions beyond the specified human wrist ranges of motion, as discussed in Section II-A, to ensure safety exercising. Preserving simplicity in the initial design, most of the exoskeleton parts have 2D outline that allows low-cost and rapid manufacturing.

The pronation/supination (PS) DOF robot joint is designed using a bayonet mount, consisting of a cylindrical male side with outer radial pins and a female receptor with matching slots. The bayonet male side with outer radial pins is actuated through a pinion gear directly connected to an actuator forming a 2:1 gear transmission. The rotation range of the joint is $\pm$ 90 degrees as illustrated in Fig. 4. The PS group rotates other 2 DOF groups in the device. The abduction/adduction (AA) DOF is provided by an electric actuator mounted directly on the side linkages rigidly connected to the bayonet male side of the PS DOF joint. The AA DOF joint rotates a transversal mechanical link supporting the device handle through bearings for smooth movements (Fig. 5). Note that, the PS joint axis is coaxial with the patient's forearm rotation axis. The flexion/extension (FE) DOF joint controls the robot handle motion using an electric actuator rotating a handle link as shown in Fig. 6. The handle is used for patient's palmar grasping during rehabilitation therapy. The distance between the handle and the FE joint axis of a patient is adjusted using the compliant link discussed in detail in Section III-B.

The initial prototype employs Dynamixel MX-106 and MX-28 servomotors as joint actuators that eliminates necessity for complex electronic circuits and joint encoders for implementing robot control algorithms. The control of

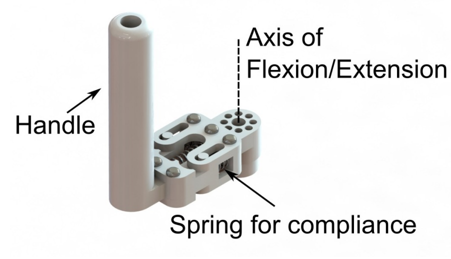

Fig. 7. Proposed design of a passive compliant handle link

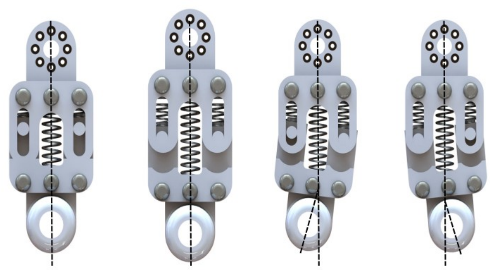

Fig. 8. Four different configurations of the compliant structure

the actuators can be performed directly from MATLAB or C/C++ programming environments.

B. Human-Robot Axes Self-Alignment

As discussed above the human-robot axes misalignment and the human wrist motion axes eccentricity cause discomfort or unsafe use of the robot. Macroscopic axes misalignment can be effectively compensated using a supplementary passive degrees of freedom (DOFs) in the kinematic chain of a exoskeleton robot [35]. In this work, the authors propose a novel design of a passive compliant link between the FE DOF joint and the robot handle as shown in Fig. 7. The compliance and flexibility is achieved by using three compression springs between the handle and the FE link. The flexible link structure allows self-alignment of the human-robot axes for different users through deviating the center of rotation and minor reserve of translation between the axes of rotation and the robot handle. The compliance of the proposed link minimizes supplementary misalignment forces during human-robot therapy, thus no discomfort or pain can be felt by the user. The rigidity in the self-aligning device can be changed by replacing the springs with appropriate stiffness.

There are four different link configurations that can take place during the therapy operation as illustrated in Fig. 8. In the first two modes, from left to right, the distance between the handle and the FE joint is adjusted as their axes are collinear. This allows to automatically adjust the structure for working with patients with different wrist and forearm sizes. The remaining two modes demonstrate the case when the handle axis is not collinear with the FE joint one, thus simulating eccentricity between the rotation axes in a human wrist. As the supplementary forces vary during human-robot therapy, the link non-rigid structure allows switching between the above nodes dynamically to minimize the applied interaction forces to the user.

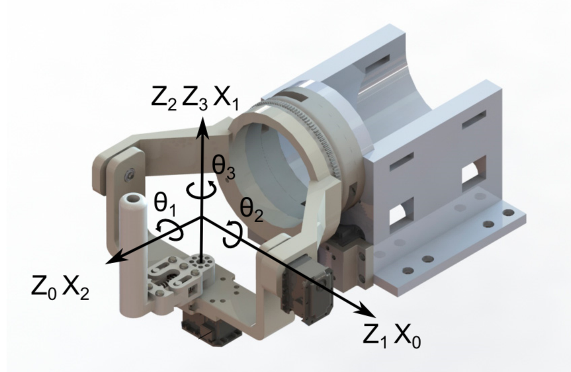

Fig. 9. Kinematic structure of NU-Wrist rehabilitation robot

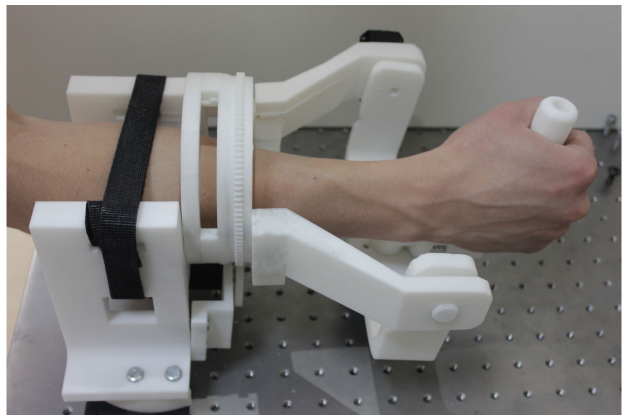

Fig. 10. A 3D printed proof-of-concept prototype of NU-Wrist rehabilitation robot tested by a healthy subject

C. Robot Kinematics

The proposed NU-Wrist rehabilitation robot provides user's wrist and forearm rotation motions. Considering the robot default position in the Fig. 9, the rotation coordinate axes for the robot 3 DOFs are assigned as follows: z_1,z_2 and z_3 coincide with users PS, AA and FE rotation axes. Thus, frame$_0$, frame$_1$, frame$_2$ and frame$_3$ stand for ground base, SP, RUD and FE groups respectively.

Frame$_1$ is rotated 90° ($\pi/2$) about its x axis to coincide with frame$_0$ x axis. Similarly, frame$_2$ rotated 90° ($\pi/2$) around its z and x axes to correspond with frame$_1$. Since, the all frames share the same origin, the translation parameters of x and z axes are zero. The Denavit-Hartenberg parameters of the NU-Wrist robot are summarized in Table I. The corresponding transformation matrix from frame$_3$ to frame$_0$ is the following:

$$T_3^0 = \begin{bmatrix} c\theta_1 c\theta_2 c\theta_3 + s\theta_1 s\theta_3 & c\theta_3 s\theta_1 - c\theta_1 c\theta_2 s\theta_3 & c\theta_1 s\theta_2 & 0 \\ c\theta_2 c\theta_3 s\theta_1 - c\theta_1 s\theta_3 & -c\theta_1 c\theta_3 - c\theta_2 s\theta_1 s\theta_3 & s\theta_1 s\theta_2 & 0 \\ c\theta_3 s\theta_2 & -s\theta_2 s\theta_3 & -c\theta_2 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

The robot design and kinematics analyses reveal that singularity conditions may occur in the case when two axes

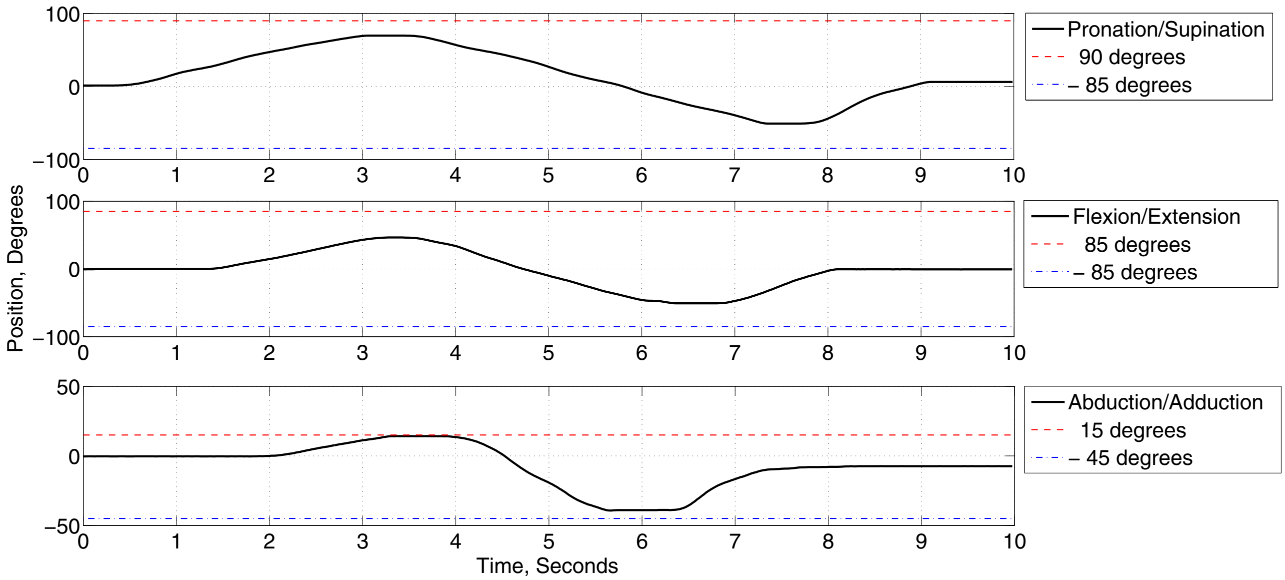

Fig. 11. Range of motions for PS, AA and FE DOSs (degrees) of NU-Wrist rehabilitation robot during active motions of a healthy subject

TABLE I

DENAVIT-HARTENBERG PARAMETERS OF NU-WRIST

i	θ_i	α_i	a_i	d_i
1	θ_1	$\pi/2$	0	0
2	θ_2	$\pi/2$	0	0
3	θ_3	0	0	0

of rotation are aligned. One can argue that FE and AA groups are prone to get into a singularity position when one of θ angles equals to $\pi/2$. However, the allowed robot range of motions are based on the human wrist rotation ranges discussed in Section II and are mechanically limited to angles less than $\pi/2$. This makes the designed robot a singularity free mechanism.

IV. RESULTS AND CONCLUSIONS

To validate the proposed robot design the first proof-of-concept prototype has been manufactured using 3D printing technology as presented in Fig. 10. Preliminary investigation has been completed focusing on evaluating on kinematic and dynamic parameters required for proper functional use of the designed robot [41].

The robot workspace of motion is tested in isolated PS, AA and FE motions on a healthy subject. Angular deviations from the actuator encoders have been recorded while the subject was performing the exercises within the maximum ranges of motion. Figure 11 presents the recorded data within 10 sec motion exercise. Next, the device reproduced the subject's motion, thus demonstrating repetitive passive therapy action. As clear from the graphs all the robot DOFs were within the physical limits of human arm motions. Specifically, a healthy subject was able to move his forearm in the range of 85° to -75° for PS activities. At the same time the FE range did not exceed ±50° range, and the AA motion of the subject's wrist was limited to the range of 15° to -45° without any extra effort applied.

Same tests conducted with several healthy subjects confirm that the compliant handle link mechanism of the robot prototype shows slight bending to either of the four configurations in Fig. 8 during active limb motions. The subjects did not feel any discomfort or applied interaction forces imposed by the robot and could freely work with the robot.

In overall, it is confirmed that the proof-of-concept prototype of NU-Wrist rehabilitation robot meets the imposed design objectives and constraints, i.e. its motion kinematics lies within the specified workspace for all DOFs. Subjective aspects like convenient handle and forearm support will be introduced in the next versions of the robot design.

In future authors plan to develop and implement impedance and assistive control strategies for different modes of operation. Furthermore, graphical user interface with virtual reality and interactive games will be implemented for quantitative performance feedback. It is employed to improve the efficiency of therapy treatments as patients will remain more focused through the often lengthy rehabilitation process.

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