A Mobile Parallel Manipulator for the Elbow Rehabilitation of Parkinsonian Patients

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***Abstract*—This study presents a two degrees of freedom (DoF) parallel manipulator that enables Parkinsonian Patients to regularly do the assigned rhythmic tasks in order to reduce the symptoms of motor disorders. Considering the elderly patients who constitute the majority of the Parkinsonians, the robot is designed to be portable to serve people to consistently take therapy at home. Moreover, the robotic platform is designed to be adjustable for any anthropometric size of a human arm in order to allow people to ergonomically perform tasks. The kinematic analysis and control of the five-bar parallel robot are carried out to ensure that users can do upper extremity coordination on the anthropometrically compatible workspace.**

***Keywords*—Parkinson's Disease, Motor Learning, Elbow Rehabilitation, Rhythmic Dynamic Task, Parallel Robots.**

I. INTRODUCTION

Parkinsonism is a neurodegenerative disease diagnosed around 6.1 million in the world [1]. Rehabilitation therapy plays an important role in retraining the motor communication skills of patients suffering from Parkinson's Disease (PD) [2]. Despite the conventional rehabilitation based therapy is still the part of the treatment process of such disease, robotic therapy has recently gained popularity in terms of objective assessment and evaluation, mobility, cost-effectiveness, and efficiency. Hence, the researchers in the neurorehabilitation robotics field are in the quest of a way to regain the upper and lower extremity function and coordination disorders in long term [3]. In particular, intensive repetitive therapy helps to recover the problematic region in the nervous system and reduce the symptoms of motor disorders.

Parkinson's symptoms, such as slowed movement, stiff muscles, impaired posture and destabilized balance due to weakened reflexes, loss of fine motor activities, and hand tremor, most of the time, hinder Parkinsonians to perform activities of daily living (ADL) [4,5]. The most common reason behind the mentioned dysfunctions is due to the neurological disorders [6]. Intensive training programs are proposed for the alleviation of the troubles, like the loss of balance of the patients [7]. In particular, one of the most prominent sign of Parkinson, the hand tremor problem, was treated as a means of intensive upper extremity training prominent sign of Parkinson, the hand tremor problem, was treated as a means of intensive upper extremity training programs such that patients were able to perform ADL, like drinking a cup of water [8].

Types of physical activity also influence efficacy of the rehabilitation on patients with PD [9]. In this particular, a study on animals of PD provided evidence that both training and learning reveal the mutual interaction between degenerative and regenerative mechanisms of the patients [10]. Moreover, such combination takes role in regaining of motor functions and preservation of neuronal structure, hence provides decrease in the rate of the neuronal loss over time [11]. These results indicate the efficacy of the rehabilitation enhanced by the motor learning activities on Parkinsonians.

Recent studies show that performance-based rehabilitation robotics during rhythmic exercises can effectively preferred in the treatment process of the upper extremity dysfunctions [12]. Rhythmic dynamic tasks are one of those to investigate the rate of human motor adaptation while performing point to point reaching movement under varying environmental conditions [13]. Along these lines, the tracking performance of the patients represented considerable improvements with respect to the initial stages of their trainings [14]. Considering the aforementioned findings, these activities helps patients with PD restore their motor functions as they require continuous planning and control by the user. Observing patients while regularly doing such exercises is also a very informative cue about their follow-up period. Hence, designing a manipulator that allows patients to carry out such tasks is quite essential in terms of getting utmost efficiency from the rehabilitation.

In this study, we propose a mobile, adjustable and ergonomically designed 2-DoF parallel robotic manipulator that allows Parkinsonians to regularly do repetitive exercises. Such a device motivates especially the elderly patients to consistently do their daily training without requiring visiting hospitals or therapy centers. Considering the subjective evaluation and non-accurate conventional therapy techniques, proposed design not only provides accurate and objective evaluation regarding patients' follow-up phase but also consistently assist people to carry out the tasks. Moreover, the

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adjustable linkage system of the robot enables users to ergonomically adjust the size of the links based on their anthropomorphic measurement of the arm and also provides convenience in terms of transforming the robot to a compact form to make it portable. This study basically details the design criteria of the robot for the elbow rehabilitation of the patients with PD and presents the kinematic and dynamic analyses and simple control of the device.

II. Design Objectives

Capability of the parallel manipulator is an imperative design requirement of the elbow rehabilitation robot for the patients with PD. In particular, the parallel manipulator is able to provide activities associated with motor learning task. The optimal requirement of the robot is to present an anthropomorphically adjustable robotic platform in order to be compatible for any size of user. Mobility is the primary design requirement of the robotic platform. Such criterion does not oblige patients to visit physiotherapist at clinics as it is portable to put the device to any desirable place. Hence, the patients with PD can consistently and regularly utilize the device.

III. Anthropomorphically Compatible 2-DoF Parallel Robotic Manipulator

The 2-DoF robotic manipulator is composed of a five-bar linkage parallel mechanism, which is a.k.a. pantograph robot. The pantograph robot is ergonomically designed to make it compatible to any size of user. The arm-elbow anthropomorphic measures of human are the important metric to design the sufficient workspace for the patients. The linkages of the robotic manipulator are designed to be adjustable in order to provide ergonomic and effective use for the patients with PD. In order to realize the point-to-point reaching task, the maximum required distance is determined based on the average anthropometric value of male person [15] as depicted in Fig. 1.

Along these lines, the proper length for each linkage is calculated considering the min-max joint angles. Fig. 1 also represents the accessible limits of the pantograph robot. Here, the green clouds illustrates the scanned area by the half of the manipulator whereas the blue clouds represents scanned are by the other half of the robot, finally the overlapping space shows the area where the patients can do reaching exercises.

The anthropomorphically compatible workspace is realized by means of telescopic linkage mechanisms. Such a design makes the robot portable as well, as the link lengths can be shortened. The solid model of the pantograph robot endowed with the adjustable workspace and foldable platform is presented in Fig. 2.

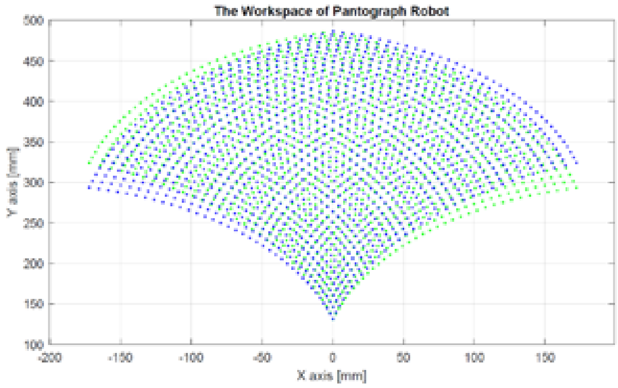

Fig. 1. The workspace of the 2DoF parallel manipulator in 2D Cartesian coordinates

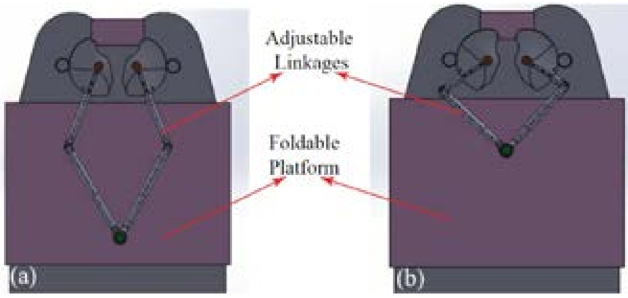

Fig. 2. Solid model of the mobile rehabilitation platform (a) Maximum allowable workspace (b) Minimum allowable workspace

The first prototype of the pantograph robot is depicted in Fig. 3. As for the manufacturing of the portable robot, the preferred material for the linkage mechanism of the robot is carbon fiber as the lightweight and durable material is necessitated to be carried by elderly patients. Since the carbon fibers are rigid enough, they provide fast response against human command. The rest of the robot is mainly produced with ABS plastic as means of 3d printer.


Fig. 3. The prototype of the adjustable mobile pantograph robot

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IV. Kinematic Analysis

The parallel robotic manipulator is designed to be utilized for the elbow rehabilitation of the patients with PD. They basically do the medial and radial rotation of their elbow to accomplish the rhythmic dynamic tasks. The forward and inverse kinematic analyses require describing an analytical relationship between the joint parameters of the pantograph robot, coordinates of each link and the end effector.

The vector loop equation of the pantograph is derived utilized by the vector summation (shown as the red line) represented in Fig. 4 and equation (1).

$$(L_1.|a_1) + (L_2.|b_1) - (L_3.|c_1) - (L_4.|d_1) - (L_0.|n_1) = 0 \quad (1)$$

Here, L_0, L_1, L_2, L_3, L_4 represent the length of each link and a_1, b_1, c_1, d_1, n_1 represent the each link's respective coordinate system. Utilizing the rotation matrices of the coordinate systems with respect to the base frame (n), the configuration level forward kinematics is derived and expressed in equation (2) and equation (3).

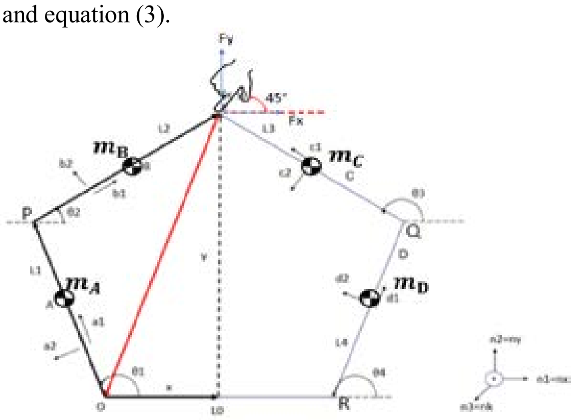

Fig. 4. Schematic representation of the pantograph

$$x = L_1 \cos\theta_1 + L_2 \cos\theta_2 \quad (2)$$

$$y = L_1 \sin\theta_1 + L_2 \sin\theta_2 \quad (3)$$

The inverse kinematic analysis is carried out by means of Newton-Raphson Method, position level forward kinematics of the robotic manipulator (equation (2) and equation (3) of end effector) and holonomic equation (1).

V. Dynamic Analysis and Control

As mentioned earlier our basic goal is to enable patients to realize reaching activities by means of the proposed platform. For a well defined trajectory of the end effector, the required joint torques need to be calculated. In this study we utilize Euler-Lagrange formulation to derive dynamic equation of the parallel robotic manipulator represented in equation (4).

$$D(\theta)\ddot{\theta} + C(\theta,\dot{\theta})\dot{\theta} + G(\theta) = \tau \quad (4)$$

,where D symbolizes the inertia matrix, C represents the Coriolis matrix, and G is the gravity vector.

Depending on the severity of the disease or improvement on the progress of the patients with PD, the robot can change the difficulty level of the tasks. In particular, patients may expose to some perturbation forces through end effector while following a trajectory. In this case, the dynamic equation is derived as expressed in equation (5).

$$D(\theta)\ddot{\theta} + C(\theta,\dot{\theta})\dot{\theta} + G(\theta) + Texternal = \tau \quad (5)$$

Here, $T_{external}$ represents the torque resulted from the external force exerted on the end effector. Utilizing the findings in the literature [16] about the maximum average level of the force can be applied to patients, the required torque for each actuator can be calculated and accordingly manipulator is controlled based on the dynamic equation in equation (5). Assuming that the external force is applied to end effector of the robot in the direction of 45^{o} with respect to x axis the comparison of the reference versus actual trajectories with the considerable error is presented in Fig. 5.

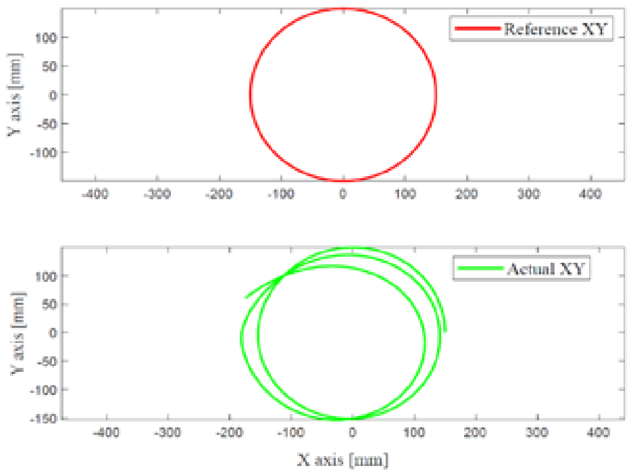

Fig. 5. Comparison of reference input (a) and actual trajectory when perturbation is applied (b)

The simulation results indicates the necessity of the controller to be able to follow the reference trajectory precisely even under random perturbations acting on the end effector. The joint space control of the pantograph robot is realized by means of the dynamic equation including control input ($T_{control}$) represented in equation (6).

$$D(\theta)\ddot{\theta} + C(\theta,\dot{\theta})\dot{\theta} + G(\theta) + Texternal + Tcontrol = \tau \quad (6)$$

The results shown in Fig. 6 indicate that the position tracking RMS error of the motors are close to zero, verifying that precise position control is carried out successfully under PI controller.

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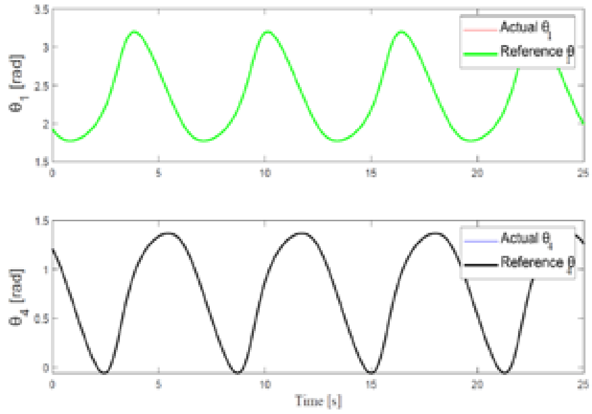

Fig. 6. Comparison of the reference and actual joint position under PI controller (a) θ_1 and (b) θ_4

The effect of perturbation observed in Fig. 5 can be avoided after applying PI controller, verifying that accurate position tracking is obtained in task space as presented in Fig. 7.

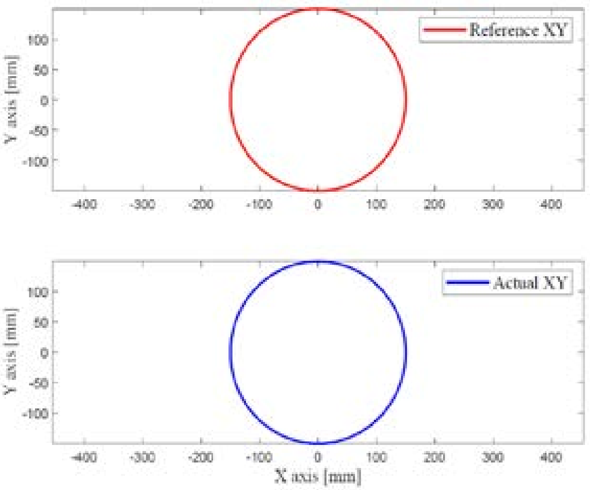

Fig. 7. Trajectory tracking performance of the robot in task space

V. Discussion and Conclusion

In this study, the design, fabrication and simulation of the mobile rehabilitation robot for the elbow therapy of the Parkinsonian patients are presented. The anthropomorphically adjustable linkages of the manipulator provide patients with PD ergonomic use. Moreover, the foldable platform together with the use of lightweight materials makes it easily portable to any place where the patients live. The implementation of all the criteria allows the patients with PD to consistently benefit from the robotic therapy. As the robotic manipulator is convenient to use for the rhythmic dynamic tasks, it is anticipated that such a device helps to restore the motor functions of the patients after its regular use.

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