Development of A Desktop-mounted Rehabilitation Robot For Upper Extremities

Md Mahafuzur Rahaman khan
Department of Mechanical Engineering
University of Wisconsin-Milwaukee
Milwaukee, USA
Khan45@uwm.edu

Tanvir Ahmed
Department of Biomedical Engineering
University of Wisconsin-Milwaukee
Milwaukee, USA
tanvir@uwm.edu

Jaime Rafael Hernandez Pallares
Department of Mechanical Engineering
University of Wisconsin-Milwaukee
Milwaukee, USA
herna854@uwm.edu

Md Rasedul Islam
Richard J. Resch school of engineering
University of Wisconsin-Green Bay
Green Bay, WI, USA
islamm@uwgb.edu

Brahim Brahmi
Department of Electrical and Computer Engineering
Miami University
Oxford Ohio, USA
brahmib@miamioh.edu

Mohammad Habibur Rahman
Department of Mechanical Engineering
University of Wisconsin-Milwaukee
Milwaukee, USA
rahmanmh@uwm.edu

Abstract

It is estimated that nearly 16 million people are affected by stroke worldwide every year. Among them, more than 60% of individuals suffer from upper limb dysfunction. Robotic rehabilitation therapy has been proven to improve these individuals' motor ability and positively affect their recovery. In this research, Desktop-Mounted Rehabilitation Robot (DMRbot) has been developed. DMRbot is an end-effector type robot with three degrees of freedom, mounted on a desktop. It can provide passive therapeutic exercises to individuals having impaired upper-limb function. DMRbot has the capability to provide rehabilitative therapy across the whole range of upper-limb workspace. Modified Denavit-Hartenberg conventions were used for kinematic, and the iterative Newton-Euler method was used to develop the dynamic model of DMRbot. The DMRbot is maneuvered to follow any trajectory within its workspace using a linear Proportional-Integral-Derivative (PID) control technique. These trajectories are generated such that the resulting robot's motion synergistically promotes rehabilitative exercises for the patient. Experimental results show that the DMRbot can provide various passive exercises to the right and left upper limbs. In addition, it has shown great promise in delivering multi-joint upper limb motions in 2D and 3D planes.

Keywords
Robot, Rehabilitation, Upper limb, Right, Left

1. Introduction
Stroke is one of the most chronic and disabling health disorders, globally affecting around 33 million people each year (Murray et al. 2014; Benziger, Roth, and Moran 2016). Stroke frequently reduces upper or lower limb ability, and up to 85% of stroke survivors have upper limb weakness. Patients need physical therapy for regaining their daily living capabilities (ADL) after a stroke (Hsieh et al. 2017). Rehabilitation is needed in this situation. Traditional rehabilitation treatment usually exercises rehabilitation, which means that the patient executes many repetitive body movements with the assistance of doctors or professional therapists. Traditionally, stroke patients are typically provided with therapies by physical and occupational therapists during their period of hospitalization. In modern neurorehabilitation, robotic/assistive devices intervention for upper-limb rehabilitation is one of the fastest-growing fields. Novel therapeutic techniques have been introduced to promote upper extremity function, and one such technique is robotic rehabilitation.

Upper limb dysfunctions, including muscle weakness, spasm, changes of muscular tension, and problems related to multi-joint coordination, are the most frequent problems after stroke(Bleyenheuft and Gordon 2014; Henderson, Korner-Bitensky, and Levin 2007). Therefore, regaining upper extremity functions is the main goal for stroke survivors. Passive treatment involves no effort from the patient and is typically used in the early phases of post-stroke symptoms when there is no response from the impaired limb(Proietti et al. 2016). Patients with hemiplegia who have one-sided paralysis typically need passive therapy(Qassim and Wan Hasan 2020). During the robot-aided passive rehabilitation session, a robot manipulates the impaired limb of the subject and provides repeated rehab exercises (Schmit, Dewald, and Rymer 2000). The movement's trajectory is carefully designed to avoid any potential injury to the patient(Głowiński and Błażejewski 2019). Passive rehabilitation was shown to be effective in reducing spasms and stiffness in the affected limbs (Ren et al. 2012).

In practice, a therapist can take care of one patient at a given time, resulting in high demand for therapists. Due to the long-term rehabilitation program and the high cost of rehabilitation therapy in the hospital, most patients have to go home for the next step of rehabilitation after some rehabilitation treatments in the hospital (Volpe et al. 2009). Moreover, home rehabilitation may also provide patients with a comfortable and convenient living environment, and it can further reduce the psychological pressure of the patients.

1.1 Objectives
In this research, an end effector type Desktop-Mounted Rehabilitation Robot (DMRbot) has been developed with three degrees of freedom. It can provide passive therapeutic exercises to those with impaired upper-limb function, allowing them to rehabilitate over the whole range of workspace in a minimally feasible design. DMRbot can provide therapy at home, reducing travel expenses and the amount of time healthcare providers are required to devote to therapeutic sessions. Furthermore, it has showed significant promise in providing multi-joint upper-limb movements in 2D and 3D planes.

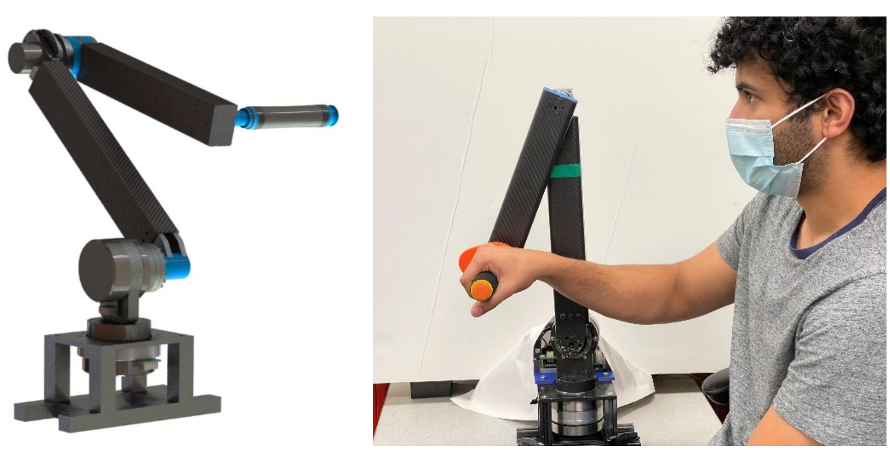
2. Literature Review
Rehabilitation robots can reduce the burden on therapists by substituting human intervention and providing ideal therapies that fulfill the following main principles of stroke rehabilitation: repetition, high intensity, and task specificity. To explore a new approach for enhancing the efficiency of stroke rehabilitation, robot-assisted rehabilitation devices have been proposed in the past few decades to provide intensive and repetitive robot-assisted rehabilitation (Gandolfi et al. 2019; Gandolfi et al. 2018; Lauretti et al. 2017). Assistive upper limb robotic devices usually consist of two types: exoskeleton and end effector. Exoskeleton robots need to mimic the joint anatomical configuration of the human upper limb, needing higher degrees of freedom and to provide a wide range of therapeutic

exercise of the upper limb(Rahman et al. 2015; Kim and Deshpande 2017). Among the few exoskeleton robots, SREx(Brahmi et al. 2021), CABexo(Xiao et al. 2017), ETS-MARSE(Rahman et al. 2015). However, most exoskeleton robots are often expensive, bulky, complex in structure, and lack portability. On the other hand, end-effector type robots are compact, lightweight, simple in structure, easily controllable. One of the main advantages of using end effector-type devices is that typically they are simpler to design and build than exoskeletons. Furthermore, the end effector type devices are easier to integrate with the patient considering the single-point contact between the two entities; thus, they are the more popular assistive devices(Cramer et al. 2019). The end-effector type therapeutic robots such as BFIAMT(Chang et al. 2007), H-man(Campolo et al. 2014), and InMotion WRIST(Karges and Smallfield 2009) are simple in structure, easily controllable.

Home rehabilitation may give patients a more pleasant and convenient living environment and a reduction in psychological stress. Making use of fuzzy logic, Su et al.(Su, Chiang, and Huang 2014) created a Kinect-enabled rehabilitation system that may be used at home without the need for a rehabilitative physician's supervision. Brokaw and Brewer(Brokaw and Brewer 2013) discussed the creation and physician evaluation of a home-based therapy system based on Kinect. The concepts of commercial games were combined with the demands of rehabilitation. Borghese et al.(Borghese et al. 2013) created a rehabilitation system using an intelligent gaming engine, and the system's trial findings revealed that it was suited for at-home rehabilitation. Villeneuve et al.(Villeneuve et al. 2017) used an inertial sensor to examine specific reduced human upper limb kinematics for home health care. The effectiveness of upper limb home-based telerehabilitation is equivalent to treatment administered in clinical settings, according to Cramer et al.(Flegal et al. 2007). Many ADL tasks, such as forking and spooning, twisting doorknobs, and manipulating small items, need fine motor control of the patient's hand and are better suited for home-based therapy. When combined with home-based exercises, patients engaging in community-based rehabilitation programs displayed improved motor function, daily activity, and social activity, according to Ru et al.(Ru et al. 2017) and Dean et al.(Dean et al. 2018). It is crucial to have appropriate movement quality during rehabilitation activities to maximize functional recovery after a stroke(Regenhardt et al. 2020). Furthermore, giving personalized feedback on the quality of exercise motions can boost motivation, enhance long-term adherence to an exercise plan, and improve clinical/home-based results(Billinger et al. 2014).

3. Overview of the DMRbot

The structural design of DMRbot, a three-dimensional SolidWorks model, is shown in Figure 1a, designed to make it a minimum viable solution for a useful robot-aided rehabilitation therapy device. This DMRbot mainly consists of the base and three links (link-1, link-2, and link-3). The joints of DMRBot are powered by Brushless DC motors (Maxon EC-45 and Maxon EC-90) coupled with harmonic drives (a gear ratio of 100:1 for all motor). The DMRbot was developed with carbon fiber and aluminum to make the robot light in weight. The rehabilitation robot system is composed of three processing units. The first is a PC unit where the top-level commands are transmitted to the end-effector robot using the LabVIEW interface. In addition to selecting the type of physiotherapy exercises and rehabilitation protocols to be performed, the performance of the end-effector robot is also assessed at the PC level; that is, it is responsible for receiving all feedback collected by the robot. The other two processing units are parts of a National Instruments PXI and input/output board with a Field Programmable Gate Array (FPGA). One of those is a board responsible for managing the end-effector system and executing the top-level command algorithms. In this case, the joint position is measured via Hall-sensors, where input/output tasks are executed at the level of this FPGA.



(a) (b)

Figure 1. (a) CAD model of DMRbot, (b) Desktop-mounted robot

4. Kinematic Modeling of DMRbot

Forward Kinematics: The position and orientation of the DMRbot end-effector relative to the joint angles are obtained from the forward kinematics of the robot. For the forward kinematics analysis of the DMRbot, modified Denavit-Hartenberg (DH){John, 1989 #43} parameters are used. To describe the location of each robot link relative to its neighbors, a coordinate frame (link frame) is attached to each link of the robot.

In order to do the kinematic analysis of this serial link end-effector type robot using these modified Denavit-Hartenberg (DH) parameters, the following link frames assignment for DMRbot is prepared in Figure 2.

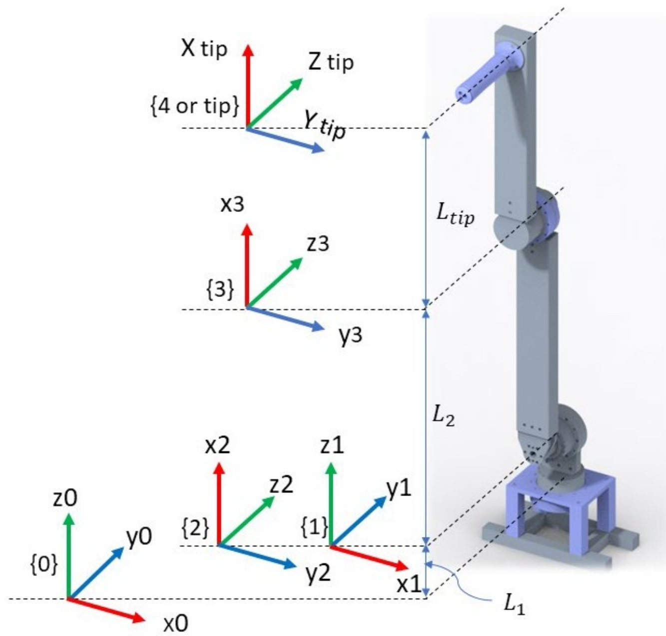


Figure 2 Coordinate frame assignment for 3DoF DMRbot

To obtain the DH parameters, it is assumed that the coordinate frames (i.e., the link-frames which map from one axes of rotation to the successive one) coincide with the corresponding joint axes of rotation, i.e., frame {1} coincides with joint 1, frame {2} with joint 2, frame {3} coincide with joint 3 and finally, frame {4 or tip} define the end-effector position of the DMRbot. The frame {0} defines the base frame (world frame) of the robot. The DH parameters corresponding to the link-frame assignment in Figure 2 are summarized in Table 1.

Table 1 Modified Denavit-Hartenberg parameters

Joint *(i)*	α_{i-1}	a_{i-1}	d_i	θ_i	Variable
1	0	0	L_1	θ_1	θ_1
2	-90	0	0	θ_2	$\theta_2' = \theta_2 - \pi/2;\ \theta_2'' = \theta_2' - \pi$
3	0	L_2	0	θ_3	θ_3
4 or Tip	0	L_{tip}	0	0	None

Where, α_{i-1} is the link twist, a_{i-1} corresponds to link length, d_i stands for link offset, and θ_i is the joint angle of the DMRbot.

The general form of a link transformation that relates frame {i} relative to the frame {i-1} is:

$$^{i-1}_{i}T = \begin{bmatrix} ^{i-1}_{i}R^{3\times3} & ^{i-1}_{i}P^{3\times1} \\ 0^{1\times3} & 1 \end{bmatrix} \tag{1}$$

Where, $^{i-1}_{i}R$ is the rotation matrix that represents the frame $\{i\}$ relative to frame $\{i-1\}$ and can be articulated as follows:

$$^{i-1}_{i}R = \begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 \\ \sin\theta_i\cos\alpha_{i-1} & \cos\theta_i\cos\alpha_{i-1} & -\sin\alpha_{i-1} \\ \sin\theta_i\sin\alpha_{i-1} & \cos\theta_i\sin\alpha_{i-1} & \cos\alpha_{i-1} \end{bmatrix} \tag{2}$$

and, $^{i-1}_{i}P$ is the vector that locates the origin of the frame $\{i\}$ relative to frame $\{i-1\}$ and can be expressed as the following:

$$^{i-1}_{i}P = [a_{i-1} \quad -sin(\alpha_{i-1})d_i \quad cos(\alpha_{i-1})d_i]^T \tag{3}$$

Using equations (1), (2), and (3), the individual homogeneous transfer matrix that relates two successive frames of the DMRbot can be found as equation (4-7):

$$^{0}_{1}T = \begin{pmatrix} \cos(\theta_1) & -\sin(\theta_1) & 0 & 0 \\ \sin(\theta_1) & \cos(\theta_1) & 0 & 0 \\ 0 & 0 & 1 & L_1 \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{4}$$

$$^{1}_{2}T = \begin{pmatrix} \sin(\theta_2) & \cos(\theta_2) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ \cos(\theta_2) & -1.0\sin(\theta_2) & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{5}$$

$$^{2}_{3}T = \begin{pmatrix} \cos(\theta_3) & -\sin(\theta_3) & 0 & L_2 \\ \sin(\theta_3) & \cos(\theta_3) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{6}$$

$$^{3}_{tip}T = \begin{pmatrix} 1 & 0 & 0 & L_{\text{tip}} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{7}$$

The homogenous transformation matrix that relates frame $\{4\ or\ Tip\}$ to frame $\{0\}$ can be obtained by multiplying individual transformation matrices that result in the generic form of equation (8) and the position of tip with respect to base frame can be found using equation (9).

$$^{0}_{tip}T = \begin{pmatrix} \sin(\theta_2+\theta_3)\cos(\theta_1) & \cos(\theta_2+\theta_3)\cos(\theta_1) & -\sin(\theta_1) & \cos(\theta_1)\sigma_1 \\ \sin(\theta_2+\theta_3)\sin(\theta_1) & \cos(\theta_2+\theta_3)\sin(\theta_1) & \cos(\theta_1) & \sin(\theta_1)\sigma_1 \\ \cos(\theta_2+\theta_3) & -\sin(\theta_2+\theta_3) & 0 & L_1 + \mathrm{L}_{tip}\cos(\theta_2+\theta_3) + L_2\cos(\theta_2) \\ 0 & 0 & 0 & 1.0 \end{pmatrix} \tag{8}$$

$where, \sigma_1 = \mathrm{L}_{tip}\sin(\theta_2+\theta_3) + L_2\sin(\theta_2)$

$$ {}_{tip}^{0}P = \begin{bmatrix} P_x \\ P_Y \\ P_Z \end{bmatrix} = \begin{pmatrix} cos\,(\theta_1)\left(L_{tip}\ sin\,(\theta_2+\theta_3) + L_2 sin\,(\theta_2)\right) \\ sin\,(\theta_1)\left(L_{tip}\ sin\,(\theta_2+\theta_3) + L_2 sin\,(\theta_2)\right) \\ L_1 + L_{tip}\ cos\,(\theta_2+\theta_3) + L_2 cos\,(\theta_2) \end{pmatrix} \tag{9} $$

5. Control

A Proportional Integral Derivative (PID) control technique has been used for initial testing and control of the developed DMRbot (Pignolo et al. 2012). The joint torque commands are expressed by Equation (10):

$$ \tau = K_P(\theta_d - \theta) + K_V(\dot{\theta}_d - \dot{\theta}) + K_I \int (\theta_d - \theta)\, dt \tag{10} $$

Where,

$\theta_d, \theta \in \mathbb{R}^{3x1}$ are the vectors of desired and measured joint angles,

$\dot{\theta}_d,\ \dot{\theta} \in \mathbb{R}^{3x1}$ are the vectors of desired and measured joint velocities,

K_P, K_V, K_I are the diagonal positive definite gain matrices,

$\tau \in \mathbb{R}^3$ is the generalized torque vector.

E is an error vector, and its derivative $\dot{E}$ given by equation (11)(12):

$$ E = \theta_d - \theta \tag{11} $$

$$ \dot{E} = \dot{\theta}_d - \dot{\theta} \tag{12} $$

Therefore, this Equation (10) has been reformulated as an error equation (13):

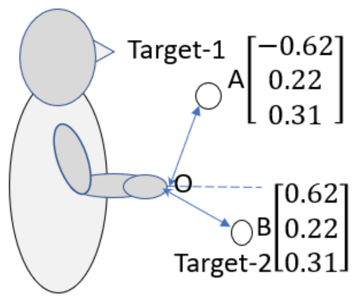
$$ \tau = K_P E + K_V \dot{E} + K_I \int E\, dt \tag{13} $$

By decoupling relation (13), the individual torque command for each joint is given by Equation (14).

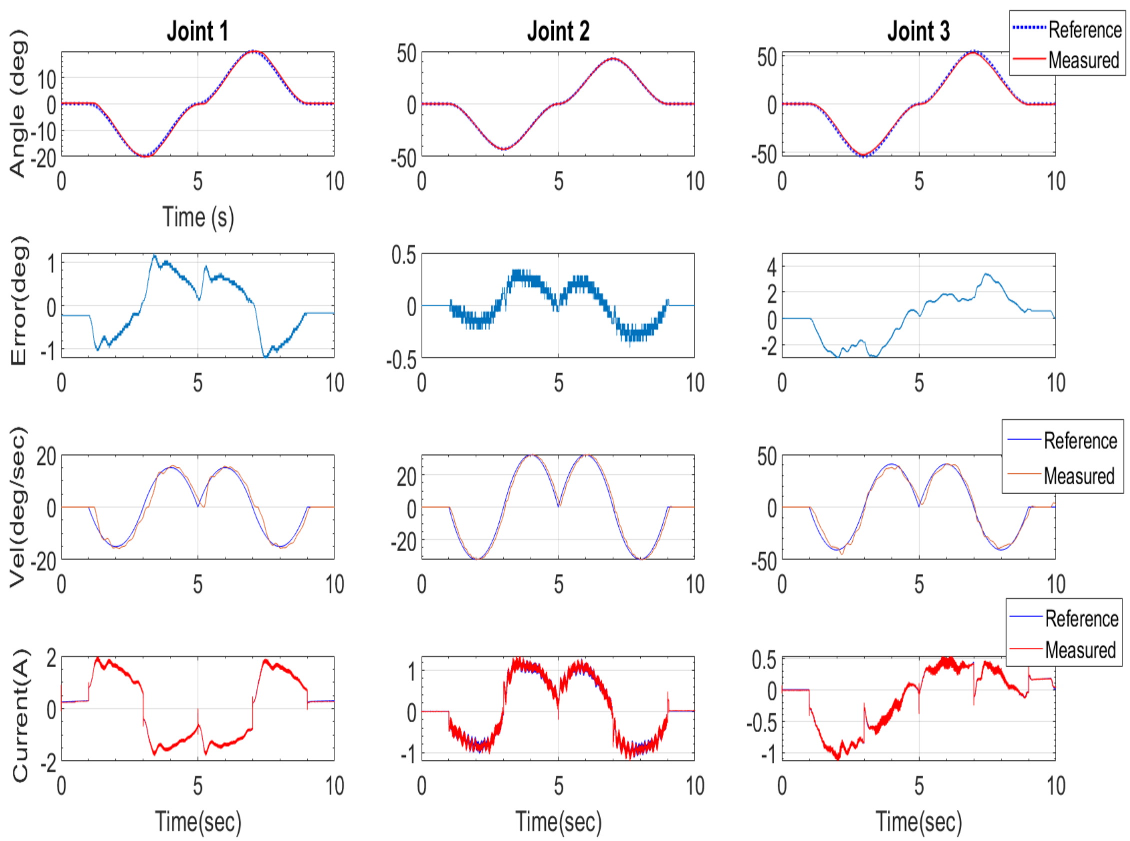
$$ \tau_i = K_{P_i} e_i + K_{V_i} \dot{e}_i + K_{I_i} \int e_i\, dt \tag{14} $$

6. Experiments and Results

The experimental setup for the DMRbot system consists of the robot and its control system set up in a desktop-mounted configuration. The robot was configured for vertical configuration for right-handed and left-handed use of the experiment, as shown in Figure 1b (right hand). For the exercises in the vertical configuration of the robot, we considered test subject-A (age: 40 years; height: 5ft 4 in; Weight: 132 lbs.). A joint-based trajectory was used during initial testing to test the PID control algorithms' performance to provide passive arm movement two different exercises with the DMRbot. The trajectory is an estimated motion therapy to stimulate the user's elbow flexion-extension motion. However, it is later observed that in an end-effector type robot, like the DMRbot, where the user's arm is not constrained, this trajectory results in multi-joints (i.e., shoulder, elbow, and wrist joints) motion of the arm. The subject sat on a chair shown in Figure 1b and operated a desktop-mounted device through pre-defined passive exercises to rehabilitate the upper limbs. The subject first remained stationary during the study while the device accomplished the necessary movements for the rehab exercises. It is repetitive motion exercises, focusing on motor rehabilitation's massed practice/repetitive practice principle. This type of exercise can increase the dosage or duration of the therapy to a patient, increasing the recovery speed.



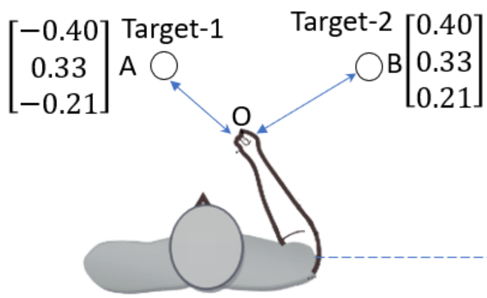
(a)



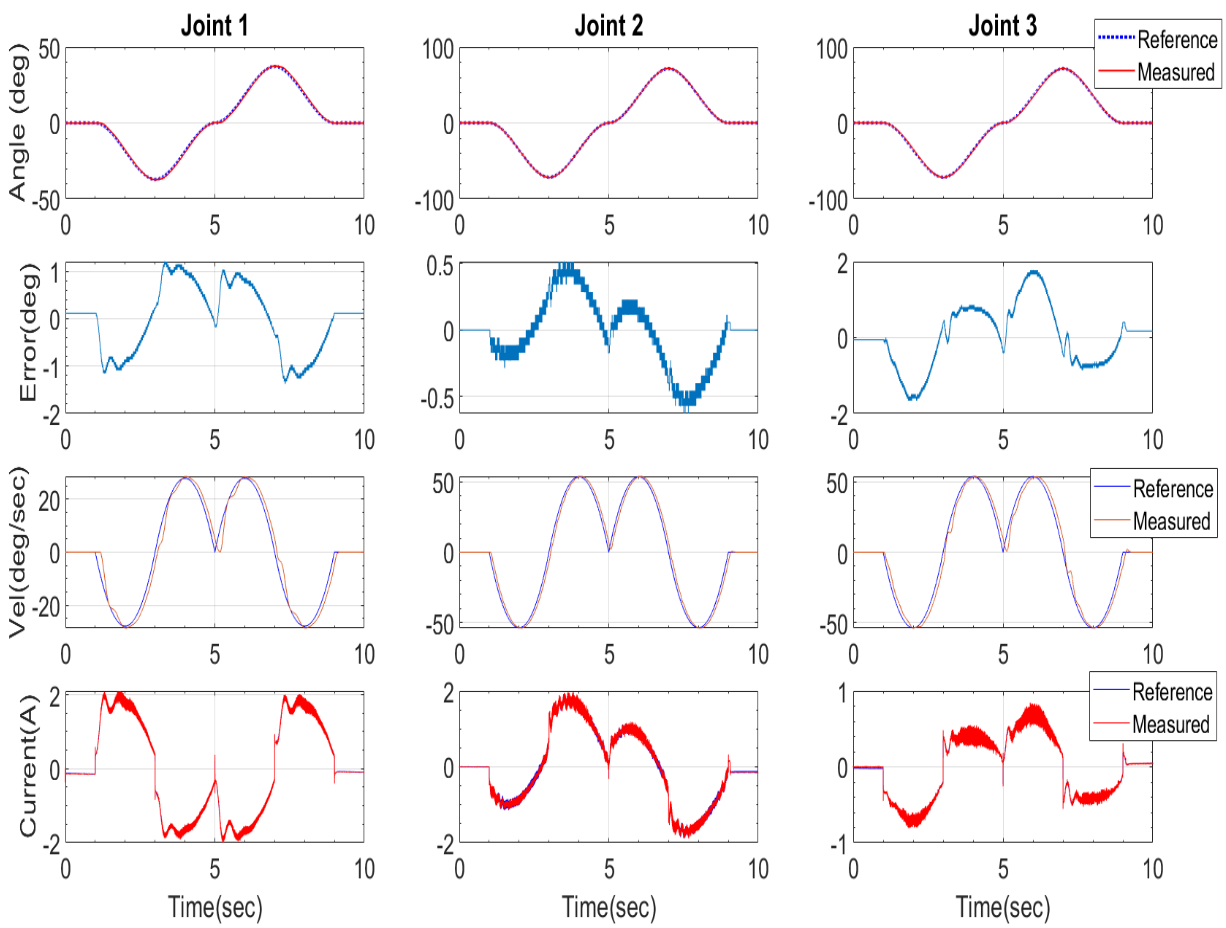
(b)

Figure 3. (a) Trajectory tracking experiments reaching different targets in 3D plane (b) Joint base trajectory

The schematic diagram of the joint base trajectory tracking exercises is given in Figure 3a; the exercise began at point-O with an elbow joint at 90° and then followed path OA to reach Target-1. This exercise aims to reach different targets one after another, which involve movement of the entire upper limb's joints. As shown in Figures 3a and 4a the exercise follows the path OA-AO-OB-BO to reach targets at two locations. The experimental results for multi joints are depicted in Figures 3b and 4b. To further evaluate the performance of the DMRbot, repetitive joint base movements were performed at different trajectories. The results demonstrate the excellent tracking performance of the controller. In this case, the maximum tracking error observed was around 3°. The experimental results presented in figure 2b and figure 3b show that the PID controller can run the robot at decently low tracking error and provide multi-joint upper limb exercises.



(a)



(b)

Figure 4. (a) Trajectory tracking experiments reaching different targets in 3D plane (b) Joint base trajectory

6. Conclusion

The upper extremity rehabilitation requires long-term, periodic training and assessment, yet many patients cannot afford the expensive treatment. It is necessary to design an effective, low-cost, and reasonable home rehabilitation and evaluation system. In this paper, we present a DMRbot, a type of end-effector robot with three degrees of freedom that can be used passively to provide therapeutic exercises to individuals with impaired upper-limb function. The kinematic model of DMRbot was developed using modified Denavit-Hartenberg conventions. A linear Proportional-Integral-Derivative (PID) control approach is used to guide the DMRbot along any desired path. Finally, the robot's ability to provide robot-assisted rehabilitation therapy following the principles of motor rehabilitation was evaluated by one healthy individual acting as the test subject, designing and completing various passive exercises. Experimental results show that the DMRbot can efficiently provide multi-joint rehabilitation therapy. Future works will include developing a control strategy to provide active-assisted rehabilitation therapy with the DMRbot.

References

Benziger, Catherine P, Gregory A Roth, and Andrew E Moran. 2016. 'The global burden of disease study and the preventable burden of NCD', *Global heart*, 11: 393-97.

Billinger, Sandra A, Ross Arena, Julie Bernhardt, Janice J Eng, Barry A Franklin, Cheryl Mortag Johnson, Marilyn MacKay-Lyons, Richard F Macko, Gillian E Mead, and Elliot J Roth. 2014. 'Physical activity and exercise recommendations for stroke survivors: a statement for healthcare professionals from the American Heart Association/American Stroke Association', *Stroke*, 45: 2532-53.

Bleyenheuft, Yannick, and Andrew M Gordon. 2014. 'Precision grip in congenital and acquired hemiparesis: similarities in impairments and implications for neurorehabilitation', *Frontiers in human neuroscience*, 8: 459.

Borghese, Nunzio Alberto, Michele Pirovano, Pier Luca Lanzi, Seline Wüest, and Eling D de Bruin. 2013. 'Computational intelligence and game design for effective at-home stroke rehabilitation', *Games for Health: Research, Development, and Clinical Applications*, 2: 81-88.

Brahmi, Brahim, Tanvir Ahmed, Ibrahim Elbojairami, Asif Al Zubayer Swapnil, Mohammad Assaduzzaman, Katie Schultz, Erin Mcgonigle, and Mohammad Habibur Rahman. 2021. 'Flatness Based Control of a Novel Smart Exoskeleton Robot', *IEEE/ASME Transactions on Mechatronics*.

Brokaw, Elizabeth B, and Bambi R Brewer. 2013. "Development of the home arm movement stroke training environment for rehabilitation (HAMSTER) and evaluation by clinicians." In *International Conference on Virtual, Augmented and Mixed Reality*, 22-31. Springer.

Campolo, Domenico, Paolo Tommasino, Kumudu Gamage, Julius Klein, Charmayne ML Hughes, and Lorenzo Masia. 2014. 'H-Man: A planar, H-shape cabled differential robotic manipulandum for experiments on human motor control', *Journal of neuroscience methods*, 235: 285-97.

Chang, Jyh-Jong, Wen-Lin Tung, Wen-Lan Wu, Mao-Hsiung Huang, and Fong-Chin Su. 2007. 'Effects of robot-aided bilateral force-induced isokinetic arm training combined with conventional rehabilitation on arm motor function in patients with chronic stroke', *Archives of physical medicine and rehabilitation*, 88: 1332-38.

Cramer, Steven C, Lucy Dodakian, Vu Le, Jill See, Renee Augsburger, Alison McKenzie, Robert J Zhou, Nina L Chiu, Jutta Heckhausen, and Jessica M Cassidy. 2019. 'Efficacy of home-based telerehabilitation vs in-clinic therapy for adults after stroke: a randomized clinical trial', *JAMA neurology*, 76: 1079-87.

Dean, Sarah G, Leon Poltawski, Anne Forster, Rod S Taylor, Anne Spencer, Martin James, Rhoda Allison, Shirley Stevens, Meriel Norris, and Anthony I Shepherd. 2018. 'Community-based rehabilitation training after stroke: results of a pilot randomised controlled trial (ReTrain) investigating acceptability and feasibility', *BMJ open*, 8: e018409.

Flegal, Katherine M, Barry I Graubard, David F Williamson, and Mitchell H Gail. 2007. 'Cause-specific excess deaths associated with underweight, overweight, and obesity', *Jama*, 298: 2028-37.

Gandolfi, Marialuisa, Nicola Valè, Eleonora Kirilova Dimitrova, Stefano Mazzoleni, Elena Battini, Maria Donata Benedetti, Alberto Gajofatto, Francesco Ferraro, Matteo Castelli, and Maruo Camin. 2018. 'Effects of high-intensity robot-assisted hand training on upper limb recovery and muscle activity in individuals with multiple sclerosis: a randomized, controlled, single-blinded trial', *Frontiers in neurology*, 9: 905.

Gandolfi, Marialuisa, Nicola Valè, Eleonora Kirilova Dimitrova, Stefano Mazzoleni, Elena Battini, Mirko Filippetti, Alessandro Picelli, Andrea Santamato, Michele Gravina, and Leopold Saltuari. 2019. 'Effectiveness of robot-assisted upper limb training on spasticity, function and muscle activity in chronic stroke patients treated with botulinum toxin: a randomized single-blinded controlled trial', *Frontiers in neurology*, 10: 41.

Głowiński, Sebastian, and Andrzej Błażejewski. 2019. 'An exoskeleton arm optimal configuration determination using inverse kinematics and genetic algorithm', *Acta of bioengineering and biomechanics*, 21.

Henderson, Amy, Nicol Korner-Bitensky, and Mindy Levin. 2007. 'Virtual reality in stroke rehabilitation: a systematic review of its effectiveness for upper limb motor recovery', *Topics in stroke rehabilitation*, 14: 52-61.

Hsieh, YW, TY Shih, KC Lin, and CY Wu. 2017. 'Upper-extremity robot-aided rehabilitation after stroke: A comparison of the arm and wrist robots', *Journal of the Neurological Sciences*, 381: 599.

Karges, Joy, and Stacy Smallfield. 2009. 'A description of the outcomes, frequency, duration, and intensity of occupational, physical, and speech therapy in inpatient stroke rehabilitation', *Journal of allied health*, 38: 1E-10E.

Kim, Bongsu, and Ashish D Deshpande. 2017. 'An upper-body rehabilitation exoskeleton Harmony with an anatomical shoulder mechanism: Design, modeling, control, and performance evaluation', *The International Journal of Robotics Research*, 36: 414-35.

Lauretti, Clemente, Francesca Cordella, Eugenio Guglielmelli, and Loredana Zollo. 2017. 'Learning by demonstration for planning activities of daily living in rehabilitation and assistive robotics', *IEEE Robotics and Automation Letters*, 2: 1375-82.

Murray, CJL, T Vos, R Lozano, Mohammad A AlMazroa, and Ziad A Memish. 2014. 'Disability-adjusted life years (DALYs) for 291 diseases and injuries in 21 regions, 1990-2010: a systematic analysis for the Global Burden of Disease Study 2010 (vol 380, pg 2197, 2012)'.

Olesh, Erienne V, Sergiy Yakovenko, and Valeriya Gritsenko. 2014. 'Automated assessment of upper extremity movement impairment due to stroke', *PloS one*, 9: e104487.

Pignolo, L, G Dolce, G Basta, LF Lucca, S Serra, and WG Sannita. 2012. "Upper limb rehabilitation after stroke: ARAMIS a “robo-mechatronic” innovative approach and prototype." In *2012 4th IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob)*, 1410-14. IEEE.

Proietti, Tommaso, Vincent Crocher, Agnes Roby-Brami, and Nathanael Jarrasse. 2016. 'Upper-limb robotic exoskeletons for neurorehabilitation: a review on control strategies', *IEEE reviews in biomedical engineering*, 9: 4-14.

Qassim, Hassan M, and WZ Wan Hasan. 2020. 'A review on upper limb rehabilitation robots', *Applied Sciences*, 10: 6976.

Rahman, Mohammad Habibur, Md Jahidur Rahman, OL Cristobal, Maarouf Saad, Jean-Pierre Kenné, and Philippe S Archambault. 2015. 'Development of a whole arm wearable robotic exoskeleton for rehabilitation and to assist upper limb movements', *Robotica*, 33: 19-39.

Regenhardt, Robert W, Hajime Takase, Eng H Lo, and David J Lin. 2020. 'Translating concepts of neural repair after stroke: structural and functional targets for recovery', *Restorative neurology and neuroscience*, 38: 67-92.

Ren, Yupeng, Sang Hoon Kang, Hyung-Soon Park, Yi-Ning Wu, and Li-Qun Zhang. 2012. 'Developing a multi-joint upper limb exoskeleton robot for diagnosis, therapy, and outcome evaluation in neurorehabilitation', *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 21: 490-99.

Ru, Xiaojuan, Hong Dai, Bin Jiang, Ninghua Li, Xingquan Zhao, Zhen Hong, Li He, and Wenzhi Wang. 2017. 'Community-based rehabilitation to improve stroke survivors’ rehabilitation participation and functional recovery', *American journal of physical medicine & rehabilitation*, 96: e123-e29.

Schmit, Brian D, Julius PA Dewald, and W Zev Rymer. 2000. 'Stretch reflex adaptation in elbow flexors during repeated passive movements in unilateral brain-injured patients', *Archives of physical medicine and rehabilitation*, 81: 269-78.

Su, Chuan-Jun, Chang-Yu Chiang, and Jing-Yan Huang. 2014. 'Kinect-enabled home-based rehabilitation system using Dynamic Time Warping and fuzzy logic', *Applied Soft Computing*, 22: 652-66.

Villeneuve, Emma, William Harwin, William Holderbaum, Balazs Janko, and R Simon Sherratt. 2017. 'Reconstruction of angular kinematics from wrist-worn inertial sensor data for smart home healthcare', *IEEE Access*, 5: 2351-63.

Volpe, Bruce T, Patricio T Huerta, Johanna L Zipse, Avrielle Rykman, Dylan Edwards, Laura Dipietro, Neville Hogan, and Hermano I Krebs. 2009. 'Robotic devices as therapeutic and diagnostic tools for stroke recovery', *Archives of neurology*, 66: 1086-90.

Xiao, Feiyun, Yongsheng Gao, Yong Wang, Yanhe Zhu, and Jie Zhao. 2017. 'Design of a wearable cable-driven upper limb exoskeleton based on epicyclic gear trains structure', *Technology and Health Care*, 25: 3-11.

Biographies

Md Mahafuzur Rahaman khan is a graduate student in the Mechanical Engineering Department of the University of Wisconsin-Milwaukee. Currently, he is working in the BioRobotics lab under the supervision of Dr. Rahman. He received his B. Sc. Engineering (Electrical and Electronics) degree from Stamford University of Bangladesh in 2019. His research interests include Digital Twin and Virtual Reality-based robotic systems for rehabilitation and assisting persons with physical disabilities.

Tanvir Ahmed is a graduate student in the Biomedical Engineering Department, University of Wisconsin-Milwaukee. Currently, he is pursuing his Ph.D. after completing his MS in Engineering from UWM and working at the BioRobotics lab, UWM as a research assistant under the supervision of Dr. Rah-man. He received his BSc. Engineering (mechanical) degree from Khulna University of Engineering and Technology, Bangladesh in 2014. His expertise includes the design, development, and control of wearable robots. He is interested in developing novel robotic systems for providing therapy and assistance to individuals with physical disabilities.

Jaime Rafael Hernandez Pallares is a graduate student in the Mechanical Engineering Department of the University of Wisconsin-Milwaukee. Currently, he is working in the BioRobotics lab under the supervision of Dr. He worked in the metalworking industry as a designer for three years in his country. Currently, pursuing an MS in engineering from UWM and working at the BioRobotics lab. UWM research assistant under the supervision of Dr. Rahman. his experiences are focused on the design, production, and development of products. Interested in developing novel robotic systems and developing products to create his own robotics company.

Md Rasedul Islam, PhD is currently an assistant professor in Richard. J Resch School of Engineering in University of Wisconsin – Green Bay (UWGB), WI, USA. As a bio-robotics researcher, he has been researching to develop novel and patient-tailored robotic system for upper limb rehabilitation of post-stroke patients. Dr. Islam, in his PhD, have engineered a 7 DOF upper limb exoskeleton robot with Ergonomic Shoulder Actuation to provide therapy for a wide range of motion. He has also worked on supervised and telerehabilitation of upper limb impairments using social robots. Besides, Dr. Islam's research interest extends to ergonomic mechanism, data-driven control, intelligent control, industrial automation and process control. Dr Islam has obtained PhD in mechanical engineering (emphasis on robotics and control) from University of Wisconsin – Milwaukee (UWM), WI, USA in 2020. At UWM, he has been awarded a prestigious Distinguished Dissertation Fellowship by graduate school. Earlier, he has graduated B.S in Mechanical Engineering from Khulna University of Engineering & Technology (KUET), Khulna, Bangladesh, in 2012. Soon after his B.S, he has joined as Lecturer in Mechanical Engineering in KUET.

Brahim Brahmi, PhD Assistant Professor with the Electrical and Computer Engineering Department, Miami University, Oxford, OH, USA. He received the B.Eng. degree from the Electronic and Automatic department of University of Science and Technology, Oran, Algeria in 2011, Master degree in computer and control system from L'viv Polytechnic National University in L'viv, in 2014. He received a Ph.D. in Engineering from the ́Ecole de technology sup ́erieure (́ETS) in Montreal, Quebec, Canada in 2019. With his thesis and specialization being in Nonlinear Control and Robotics. Currently, he is a postdoctoral research fellow at Mechanical Engineering Department, McGillUniversity. His research interests are in Nonlinear and Adaptive control, bio-Robotics, Rehabilitation robots.

Mohammad Habibur Rahman, PhD is an Associate Professor with the Mechanical and Biomedical Engineering Department, University of Wisconsin-Milwaukee, WI, USA. As Director of the BioRobotics Lab at the University of Wisconsin-Milwaukee, he brings the resources and expertise of an interdisciplinary RD team. For more than 15 years he has been researching mechatronics/robotics with emphasis on the design, development and control of wearable robots, collaborative robots, and mobile robots. He received a BSc Engineering (Mechanical)degree from Khulna University of Engineering Technology, Bangladesh in 2001, a Master of Engineering (bio-robotics) degree from Saga University, Japan in 2005 and a PhD in Engineering (bio-robotics) from ́Ecole de technology sup ́erieure (ETS), University ́edu Qu ebec, Canada in 2012. He worked as a postdoctoral research fellow in the School of Physical and Occupational Therapy, McGill University (2012–2014). His research interests are in bio-robotics, exoskeleton robot, intelligent system and control, mobile robotics, nonlinear control, control using biological signals such as electromyogram signals. Dr. Rahman has served as a Guest Editor/Associate Editors and on the editorial board of several journals, including Frontiers in Robotics and AI: Biomedical Robotics.