Resist-as-Needed ADL Training With SPINDLE for Patients With Tremor

Nikhil Tej Kantu, *Student Member, IEEE*, Ryan Osswald, Amit Kandel, and Jiyeon Kang, *Member, IEEE*

***Abstract*— Individuals with neurological disorders often exhibit altered manual dexterity and muscle weakness in their upper limbs. These motor impairments with tremor lead to severe difficulties in performing Activities of Daily Living (ADL). There is a critical need for ADL-focused robotic training that improves individual's strength when engaging with dexterous ADL tasks. This research introduces a new approach to training ADLs by employing a novel robotic rehabilitation system, Spherical Parallel INstrument for Daily Living Emulation (SPINDLE), which incorporates Virtual Reality (VR) to simulate ADL tasks. The study results present the feasibility of training individuals with movements similar to ADLs while interacting with the SPINDLE. A new game-based robotic training paradigm is suggested to perform ADL tasks at various intensity levels of resistance as needed. The proposed system can facilitate the training of various ADLs requiring 3-dimensional rotational movements by providing optimal resistance and visual feedback. We envision this system can be utilized as a table-top home device by restoring the impaired motor function of individuals with tremor and muscle weakness, guiding to improved ADL performance and quality of life.**

***Index Terms*— Tremor, dexterity training, strength training, robotic rehabilitation, training activities of daily living.**

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This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Institutional Review Board of the University at Buffalo under Application No. STUDY00004726.

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I. Introduction

TREMOR is an involuntary, rhythmic, oscillatory movement of a body part [1]. It can be characterized by postural, rest, and action tremors manifested by the upper extremities, lower extremities, vocal cords, or head. Tremor can be classified based on clinical features and etiology [1]. Pathological tremor arises in case of injury and disease of the brain, it is typically severe enough to impede daily activities and hinder social interactions [2]. More than 65% of those affected by tremors in the upper limbs present severe difficulties in performing activities of daily living (ADL) [3], [4]. In severe cases, tremor occurs with sufficient amplitude to obscure most underlying voluntary movements [5], [6].

Essential tremor (ET) is an isolated tremor syndrome of bilateral, upper limb action tremor of at least 3 years duration, with or without tremor in other locations [1]. About 7 million people are affected by ET [7], which has been one of the most common movement disorders in adults [8]. ET affects fine motor control of the hands, affecting ADLs such as eating, drinking, and writing [9]. Typically, tremors are treated with medication, although up to 53 % of patients stop taking their medications because of side effects or a lack of effectiveness [10]. Tremor reduction with prescribed drugs such as Propanolol and Primodone is reported around 50% or less, often accompanied by side effects [9]. Botulinum toxin can be used to treat ET, but the efficacy of tremor control has been limited and has significant side effects of weakness [9]. Several surgical treatments are pursued for treating tremors: radio-frequency lesioning, gamma knife radiosurgery, and Deep Brain Stimulation (DBS). DBS is a highly productive therapeutic intervention for alleviating tremors, slowness, and stiffness [11]. However, a significant proportion of individuals affected by ET may not be suitable candidates for DBS due to many factors, encompassing their prevailing medical condition and advanced age [12], [13]. Specifically, DBS has several negative consequences, including cognitive behavioral and mental issues, prolonged recovery time, and high surgical risks, which impact 48% of patients throughout their lifetime [14], [15]. Thus, researchers experimented with other alternatives for the tremor treatment, such as cooling the limbs, vibration treatment, transcranial magnetic stimulation, electrical sensory stimulation, and functional electrical stimulation [10]. However, these methods could not achieve a significant positive effect compared to DBS [9].

Another alternative method is resistance-based physical therapy, frequently employed to reduce tremors [16], [17].

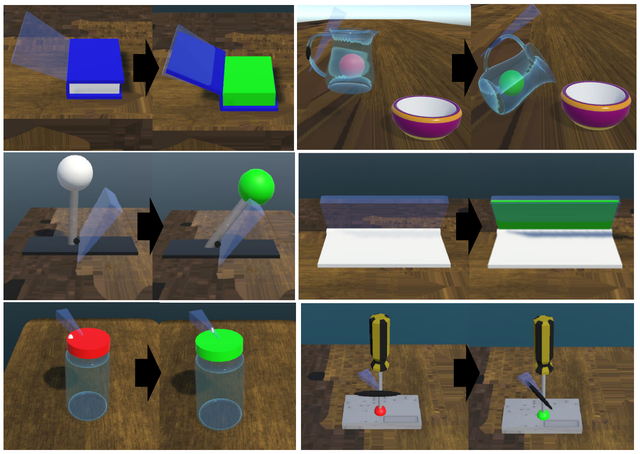

Fig. 1. Six representative game-based ADL tasks in the VR environment. The tasks are designed based on actual object manipulation characteristics. Each task has a desired target posture of the object.

Researchers [18], [19], [20] have demonstrated that resistance training decreases tremors and improves dexterity and strength in ET patients [19]. These physical therapy programs involved several weeks of dumbbell bicep curls and wrist flexion/extension exercises. The repetitive resistive training and task-based exercises stimulated the motor system by separating the activity of agonist and antagonist upper limb muscles of ET patients [21], [22]. Although these training paradigms have shown some promising results in upper limb movements, the training effect outside the clinic was moderate. This is because the residual impairments in muscle weakness and coordination disorder were still affecting ADLs of ET patients [23], [24]. To continue training at home and in community settings, a repetitive and interactive training methodology is highly desired to evaluate current performance and provide optimal training for each individual.

Many robotic devices were developed to promote repetitive upper limb resistive and dexterity training [25]. These devices employ impedance-based methods to enable trajectory-based movements [26]. The systems can be classified into two categories: exoskeleton type and end-effector type. Exoskeleton type systems include a 6-DOF SEA exoskeleton Harmony [27], which provides resistive force proportional to the error in the trajectory-based training environment. Its joint-space torque controller allowed training with low inertia and a wide Range Of Motion (ROM). A 5-DOF exoskeleton, MAHI Exo-II [28], [29], was developed to establish resistance-based elbow and wrist movement training. These resistance-based rehabilitation robots were developed for reaching tasks but were not explicitly designed for ADL training. End-effector type systems include MIME [30], a tabletop robotic system that employs an active constrained movement mode to enable strength training. CDULRR [31], a cable-driven system integrated with a performance-based hybrid controller, was developed to tailor the task difficulty in resistive, assistive, and restrictive modes. The virtual damping was manipulated proportionally to the participant's performance to promote intensive dynamic training. Low tracking error enabled resistive mode to increase the task intensity. A tremor-specific study [32] presented the effectiveness of a 2-DOF

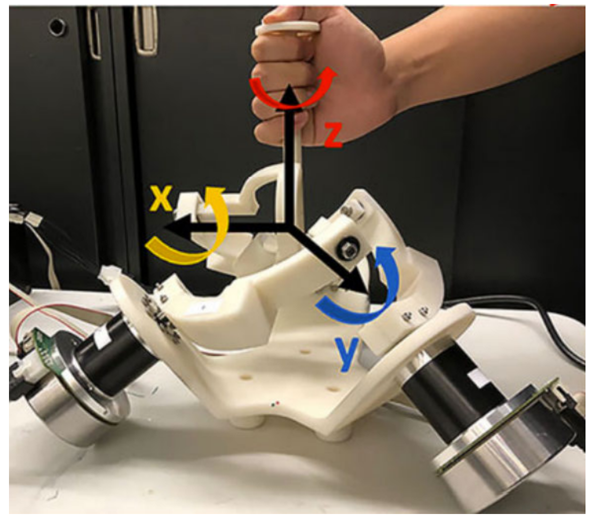

Fig. 2. Prototype of the SPINDLE. Three-dimensional rotations of SPINDLE are displayed with the X (roll), Y (pitch), and Z (yaw) axes.

planar robot for upper limb strength training in patients with Multiple Sclerosis (MS). To enable resistive training, the robot generated resistive forces against the participant's movements. Following training, Tremor Severity Scale [33], Nine Hole Peg Test [34], and Action Research Arm Test [35] showed significantly reduced tremors, enhanced limb movements and functional ability. However, most robotic systems with resistance training capabilities were not designed for practicing ADL-specific tasks, which has been a critical factor in carrying over the training effect on ADL performance. Studies have shown that training with ADL-specific tasks significantly improves functional ability compared to general upper limb training [36], [37]. Therefore, ADL-specific robotic devices are highly desired to promote a better carryover effect.

In the past, researchers developed robotic devices to establish ADL-specific training. An exoskeleton-based device, ARMin III [38], revealed improved motor functions through ADL-based robotic training. Three ADLs (cooking, cleaning, and using a ticket machine) were designed in a VR environment. The cooking task was designed to pick & drop food into a pan, the cleaning task aims to increase the user's horizontal reach by wiping the table, and the ticket machine task involves inserting coins to train the user's wrist and fingers. The user's joint ROM, end-effector mean, peak velocity, and task execution time were quantified to measure the training effect of these tasks. With the Armeo Spring system (Hocoma AG) [39], a 5-DOF exoskeleton-based robot, training ranged from gross motor movement, such as cleaning a stove top, to precise movement, including watering flowers or picking up an egg. The task difficulty of this system was tailored based on the participant's performance (task completion time and ROM). However, these systems have a limited ROM compared to ADL movements [40]. To enable natural ADL-based robotic training, ADAPT (ADaptive and Automatic Presentation of Tasks) [41] was developed to support end-effector-based ADL training, designed for 1-DOF rotating ADL tasks. Its capability to perform rotational movements and modify task complexity based on participant performance provided effective ADL

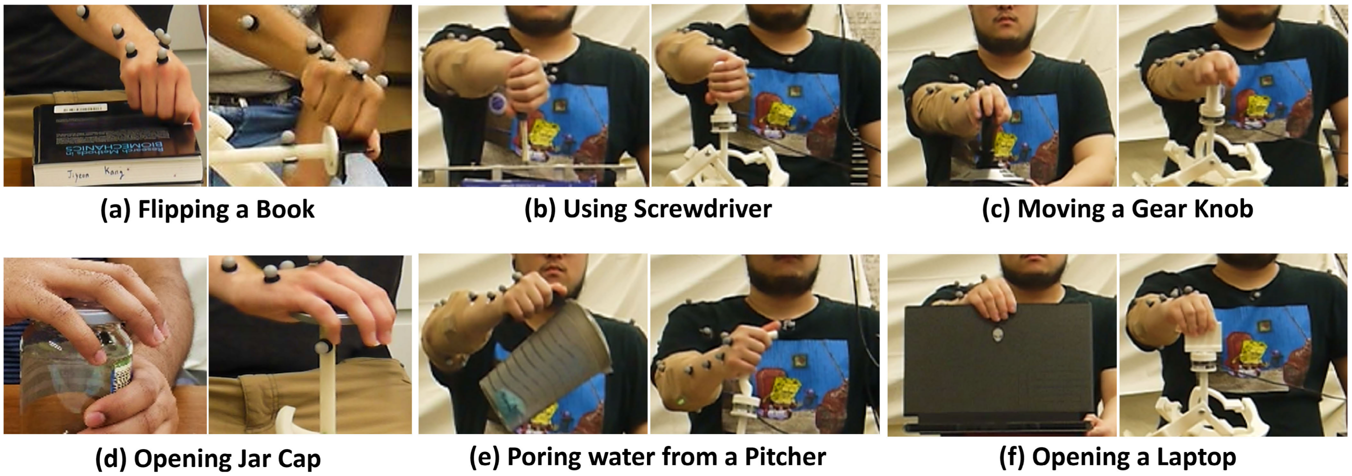

Fig. 3. Six representative ADLs were performed with the natural objects and SPINDLE; (a) Flipping a book, (b) Using a screwdriver to tighten and loosen a screw, (c) Moving a gear knob, (d) Opening and closing a jar cap, (e) Pouring water from a pitcher into a cup, and (f) Opening the laptop.

training to the participant. However, ADAPT tasks could only be performed on a single plane, limiting the training of upper limb movements required for everyday ADLs [40]. Another ADL-based upper limb rehabilitation study [42] employed two modular robotic devices: AMADEO (Finger-hand robot) and DIEGO (Arm-shoulder robot). The integrated system of these modules has facilitated the training of complicated ADLs by establishing intuitive visual feedback using VR [42]. For example, Apple Farmer task focuses on training in vertical reaching movements, and Elevator Basic task involves training for wrist rotation. Although the system has a wide training scope, its bulky, rigid architecture and expensive cost make its use in home settings impractical.

There are limitations with current robotic technologies to enable ADL-based training, and only a few studies focused on tremor reduction through upper limb strength training. Currently, no devices are available that specifically target ADL-based strength training and aim to enhance dexterous functional movements in patients with tremors [25]. Thus, an ADL-specific robotic rehabilitation system that enables interactive ADL training for ET patients is highly desired to address the limitations of current systems.

A robotic rehabilitation system must integrate two characteristics to strengthen muscles with tremors and enhance their ADL performance. The first aspect is to serve as a measurement tool for ADLs to accurately simulate a broad range of real-world tasks and measure baseline ADL performance, which is crucial for personalized robotic treatment. The second aspect is to serve as a training tool to provide optimal resistance for strength training and practice coordination of the upper limb joints. Identifying the optimal resistance for the training is crucial because excessive load can lead to early fatigue and reduce the participant's motivation. In contrast, meager resistance will not provide enough resistance to dampen out the tremor and strengthen the upper limbs.

As an ADL robotic trainer, we developed a parallel manipulator, SPINDLE (Spherical Parallel INstrument for Daily Living Emulation), shown in Fig. 2, that allows three-dimensional rotations with a wide ROM [43], [44]. ADL tasks in SPINDLE were designed for the participant to position SPINDLE in a particular end posture to practice both reaching and precision tasks. Virtual Reality (VR) is integrated into ADL tasks to provide visual cues and realistic performance, as shown in Fig. 1. We need a resist-as-needed training strategy to provide adaptive resistive training with SPINDLE to enhance neurophysiological factors, including strength, isolation of agonist & antagonist muscles, motor control, coordination between joints, and ROM. An adaptive control methodology depicted in Fig. 3 has been developed to provide personalized optimal resistance to train individuals with tremors.

This study presents three crucial objectives: i) the physiological comparison when performing six representative tasks in SPINDLE ADL and real-world ADL across kinematics, ii) landscaping of virtual damping vs task score to characterize the task performance when the participant was given different resistance, and iii) incorporating VR to perform each task with visual cues and vivid experiences. Nine healthy participants with simulated tremors conducted six representative ADLs. We hypothesized that there would be an optimal damping, such that participants with tremors could perform the given task most effectively. We expected that this optimal damping would be different for each task. The adaptive nature of the suggested training approach facilitates the customization of task difficulty based on the user's performance, promoting sustained motivation over extended training periods through minimizing the monotony and frustration often associated with repetitive therapy. Moreover, this approach has the potential to optimize neuroplastic changes [45].

II. Methods

A. Participants

The Institutional Review Board of the University at Buffalo approved the experimental protocol (STUDY00004726, Approval date: 10/19/2020). All nine healthy participants (1F/8M, age 24 $\pm$ 3 years, height 5 ft 6.5 $\pm$ 4 inches, weight 79.75 $\pm$ 20 kgs) signed the consent form approved by the IRB. Each participant wore a VR Headset, 18 reflective markers,

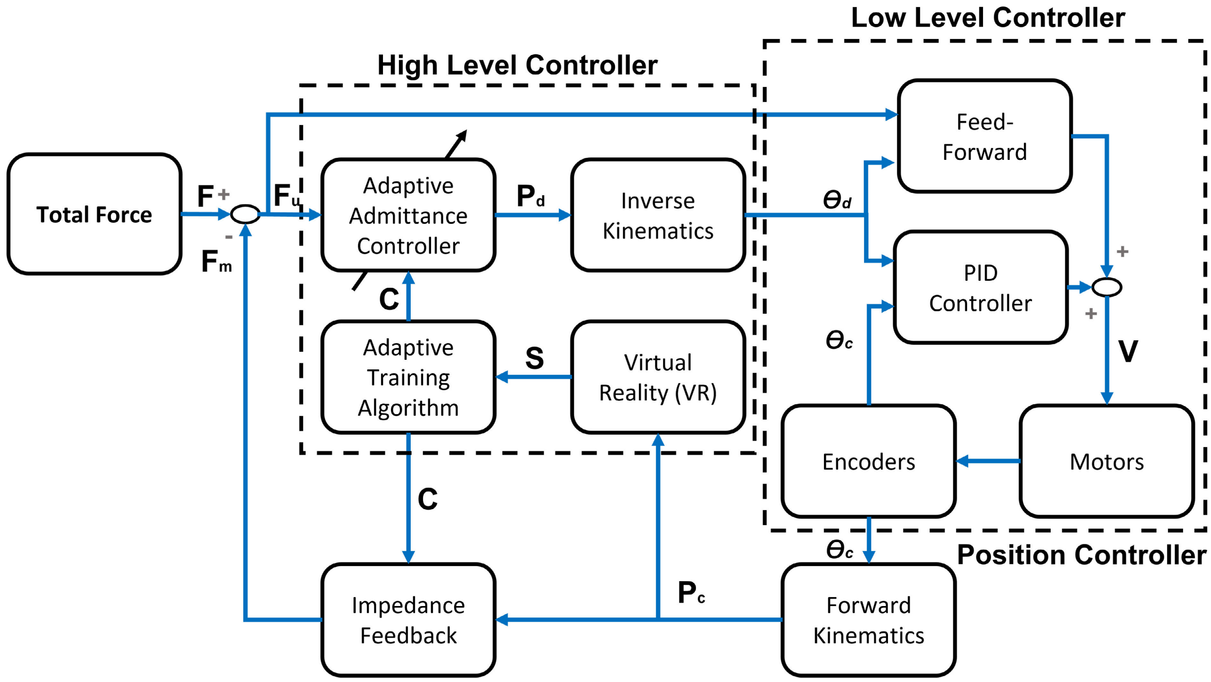

Fig. 4. Block diagram of the control architecture. **F** is the total exerted force on the end-effector, $\mathbf{F_u}$ is the subject's intended force, and $\mathbf{F_m}$ is the force exerted by the manipulator. $\mathbf{P_d}(\mathbf{X_d}, \mathbf{Y_d}, \Phi_\mathbf{d})$ is the desired end-effector posture, θ_d provides the desired motor positions, $\mathbf{P_c}$ $(\mathbf{X_c}, \mathbf{Y_c}, \Phi_\mathbf{c})$ is the current end-effector posture, and θ_c denotes current motor positions. **S** is the score quantified after each trial in the VR environment, **C** is the virtual damping that controls the viscous force applied by the system, and **V** is the voltage applied to motors.

and 11 sEMG sensors on the upper limb. As shown in Fig. 3, all participants performed six ADLs designed with the robot (SPINDLE) and natural objects. The participant performed the SPINDLE task by wearing a VR headset to visualize the target location and posture to reach. Potential participants were excluded if they were 18 or younger or if they had any significant self-reported visual or hearing impairments that would prevent them from completing the study protocol.

B. System

SPINDLE (Spherical Parallel INstrument for Daily Living Emulation) is a robotic rehabilitation device that provides resistive forces in 3-dimensional rotations.

This parallel manipulator is incorporated with a 6-axis force/torque sensor (ATI Mini 45) and a Virtual Reality System (HTC VIVE Pro) to enable an interactive ADL rehabilitation experience.

1) Hardware: The SPINDLE design is a 3-RRR spherical parallel manipulator that facilitates 3-dimensional rotational movements. It is designed to be a tabletop device installed next to hospital beds, homes, community centers, etc. This two-linkage architecture of the manipulator connects the bottom base and the top base of the parallel mechanism. The manipulator's bottom base connects the proximal links and the motors with encoders, as shown in Fig. 2. The manipulator can enable an around 180° range of rotation along all 3 DOF axes (i.e., roll, pitch, yaw). An ATI Mini 45, a 6-axis force/torque sensor (ATI Industrial Automation, North Carolina, USA), is installed at the handle to measure the human-robot interactive force data. This data is used to mimic the physical characteristics of virtual objects by the motors. The manipulator is controlled by three Electronic Commutation (EC) 90 flat motors (Maxon Inc., Switzerland) powered by three ESCON 70/10 controllers (Maxon Inc., Switzerland). An amplitude of −90° to +90° can be achieved along the X, Y, and Z axes with maximum torques indicated as in [43]. The dimensions of the SPINDLE are 427 mm (H) × 400 mm (W) × 348 mm (L), and it weighs about 4.5 kg. This system operates under the command of a remote-controlled PC to myRIO 1900 (National Instrument Inc., Texas, USA) at 1000 Hz.

2) Control Architecture: To emulate the physical characteristics of natural ADLs with SPINDLE, a haptic interface is highly desired to emulate ADLs at different intensity levels. This study proposes a novel adaptive haptic controller, which controls the SPINDLE by tailoring the task intensity based on the participant's performance in the virtual environment. The haptic controller architecture of the SPINDLE is presented in Fig. 4. The high-level controller includes a participant-specific adaptive training algorithm that tailors the viscous force (damping factor) based on the participant's ADL performance in the VR environment. The low-level controller operates the joint-space positions of the device with a PID controller with respect to the position feedback. The integrated feed-forward model is proportional to the participant's force on the haptic knob and the end-effector position. It enables smoother task-space intervention and provides adaptive robustness to the system by minimizing the response time, inertia, and back-drivability. The feed-forward term activates when the end-effector error exceeds the ± 10 degree threshold. The low-level controller is executed at 1000 Hz, and the high-level controller operates at 300 Hz. The controller also simulates the tremors to mimic ET patients. A sinusoidal noise input

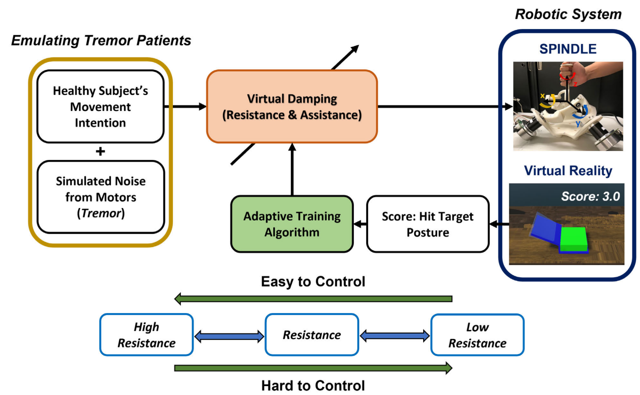

Fig. 5. Overview of the upper limb rehabilitation system. The haptic controller receives the participant's intended force as input, and the resulting end-effector manipulation is visualized in the VR environment. The participant's ability is assessed based on their score. The adaptive algorithm tailors the damping levels based on the obtained score for optimal resistance.

at 4 Hz is continuously provided to the task space to mimic the patients with tremor [46].

a) Adaptive admittance controller: This controller is designed to generate the desired task-space position $\mathbf{P_d}(\mathbf{X_d}, \mathbf{Y_d}, \Phi_\mathbf{d})$ trajectories based on the participant's exerted force. The adaptive training algorithm controls the viscous force by tailoring the damping factor $\mathbf{C}$ to enable ADL training at different intensity levels, Eq. (1). This adaptive virtual damping establishes the linear relationship between the participant's force, $\mathbf{F_u}$ and the resultant velocity of the end-effector $\dot{\mathbf{P}}_\mathbf{d}$, which is integrated with respect to time to compute the desired end-effector position $\mathbf{P_d}(\mathbf{X_d}, \mathbf{Y_d}, \Phi_\mathbf{d})$. Furthermore, the output is transformed to the inverse kinematics of the SPINDLE [43] to compute the real-time joint-space trajectories.

$$\dot{\mathbf{P}}_\mathbf{d} = \frac{\mathbf{F_u}}{\mathbf{C}} \tag{1}$$

b) Position controller: Based on the commanded desired position input $\mathbf{P_d}(\mathbf{X_d}, \mathbf{Y_d}, \Phi_\mathbf{d})$, the task space position controller computes desired joint space positions through inverse kinematics. The desired joint angles of lower proximal links coupled with the motors are inputs for the low-level PID controller to maintain the desired joint positions. The resulting task space position of the haptic knob is calculated through forward kinematics. This task-space output is utilized in the VR environment to visualize the intended movement for ADL-based training. This system overview is shown in Fig. 5.

c) Impedance feedback: This feedback controller provides the resultant force exerted by the system on the user at the user interface by utilizing the position change input provided by the forward kinematics. This feedback loop established the coupled stability of the system [47]. The current position $\mathbf{P_c}(\mathbf{X_c}, \mathbf{Y_c}, \Phi_\mathbf{c})$ is the input for this controller, the same virtual damping $\mathbf{C}$ is utilized by the adaptive training algorithm, and the output generated will be the force exerted by the system $\mathbf{F_m}$ (Eq. 2). As shown in Fig. 4, the total force exerted on the system $\mathbf{F}$ is subtracted with $\mathbf{F_m}$ to obtain the user-intended force $\mathbf{F_u}$.

$$\mathbf{F_m} = \dot{\mathbf{P}}_\mathbf{c}\mathbf{C} \tag{2}$$

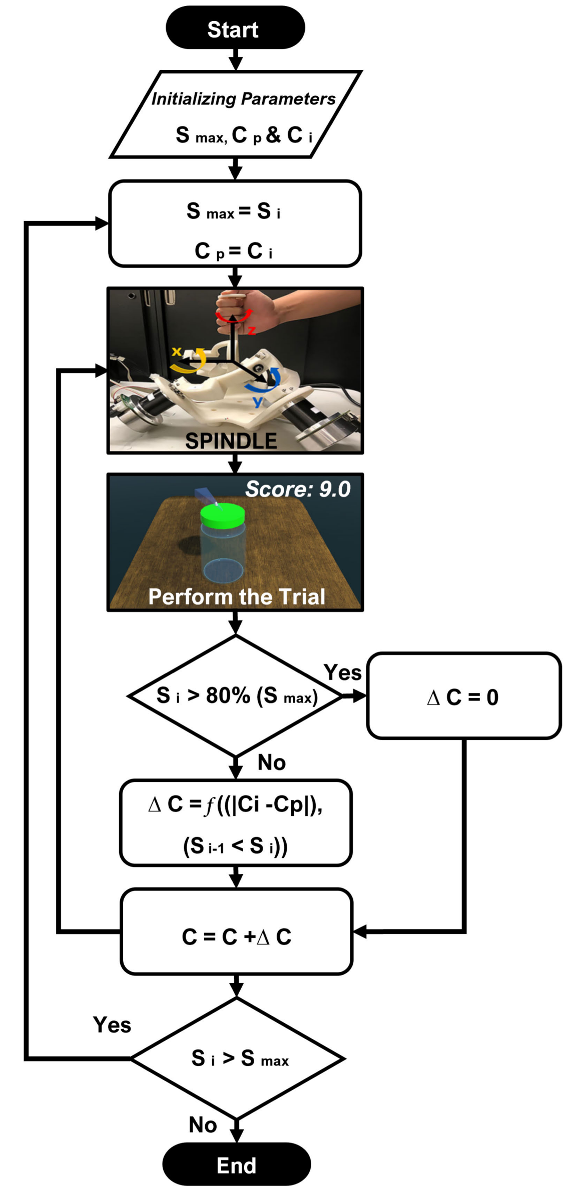

Fig. 6. Flow chart of adaptive training algorithm; tailors damping factor proportional to participant's score S_i. C_i is the current iteration damping value, C_p is the identified performance damping region from manual trials, and S_{max} is the identified maximum score from the previous trials.

d) Adaptive training strategy: The game-based VR environment indicates a target posture for every ADL task. Participants were required to reach and match the target posture to improve their score. The score is the amount of time in which the participant can maintain the target posture. The resultant score reflects the participant's ability to perform the task at that certain intensity level. Based on the score, the viscous force of the system is changed by tailoring the virtual damping $\mathbf{C}$ of the system, as shown in Fig. 6.

In this adaptive training strategy, virtual damping is explored in two methods to identify the optimal resistance (damping level). The first method initializes the training from the low resistance level (lowest virtual damping) and drives the participant towards high resistance based on the participant's task performance (i.e., previous trial score). Similarly, the second method begins the training at a high resistance level (high virtual damping) and gradually reduces the resistance depending on the performance.

The algorithm initializes the performance damping region $\mathbf{C_p}$ and the maximum score $\mathbf{S_{max}}$, which are identified from manual trials (i.e., preliminary parameter sweep trials). These parameters are defined with respect to each user's performance. The initial iteration damping value $\mathbf{C_i}$ is then set to either the lowest or highest damping value depending on the first or second method. Users will perform the trial, and the score is updated at the end of each trial. The score $\mathbf{S_i}$ and damping value $\mathbf{C_i}$ of the current iteration are updated using the algorithm logic in Fig. 6. This search continues for six iterations to determine their optimal resistance. The adaptive training algorithm facilitates tailoring the damping factor $\mathbf{C_i}$ proportional to the participant's score $\mathbf{S_i}$ [48]. If the current iteration score surpasses the previous score, algorithm updates the performance-damping region $\mathbf{C_p}$ to current region and updates maximum score $\mathbf{S_{max}}$. This adaptive training strategy must be performed once before the start of the training. Further, it will be repeatedly performed when the participants improve their motor function or change the characteristics of the tremor (i.e., frequency of the tremor) over time.

C. Human Experiment Protocol

1) Procedure: Participants wore reflective markers on their upper body so that a motion capture system could record their movement. Ten motion capture cameras (Vicon, UK) were used to detect their motion. Similarly, surface electromyography sensors (Delsys, MA) were attached to the participants' skin to record muscle activation during ADL. Study team members showed a tutorial video of each activity and performed live demonstrations to help the participants understand the task. Later, participants practiced task trials for about 5 minutes until they felt comfortable with the experiment with the robotic device and the virtual reality goggles. After the participants were equipped for the trials, the recording started, and participants performed the natural ADLs to the beat of a metronome at 60 bpm. When the participant aligns their hand on the haptic knob, force detection on the force/torque sensor will automatically trigger the VR game environment to begin the trial. Tasks were repeated 10 times, and a 5-minute break was provided between different tasks.

The SPINDLE end-effector was positioned at the same level and orientation as the natural ADL objects. This study examined six ADLs: flipping a book, pouring from a pitcher, opening a laptop, moving a car gear, opening a jar, and screwdriver activities. After the participants were prepared for the activity (EMG sensors and reflective markers were placed), they were requested to align their distal limb with the device's vertical axis. The experiment controller provided particular instructions for various ADL types. For all participants in this study, these activities were completed with simulated tremors to resemble patients with tremors. The SPINDLE controller generated simulated tremors through a sinusoidal noise with 4 Hz [49]. The tremors were continuously provided during the tasks.

Presented SPINDLE ADL trial results were quantified in a fixed period of 20 seconds. The score represents the time during which the user successfully maintained the target posture within the three-dimensional task space of the SPINDLE. The score is influenced by both dynamic & static components of the task. The dynamic evaluation includes the time required to transition from the initial position to the target posture at the onset of each respective ADL activity. The static element is the user's ability to maintain the target posture for an extended period (this evaluates their dexterity skills). After all trials, the user's feedback is obtained by asking them consistent questions like 'How do you feel about the system?' or 'What did you like about the system?'

2) Six ADL Tasks: Six tasks were randomly assigned to the participant. The task score was calculated based on the participant's ability to maintain the target position in the SPINDLE's VR environment. For each task, a target posture is visually displayed, and the participant needs to move the handle to the target posture. The score assessed the participant's ability to complete the task at a specific damping level. The total time the participant could maintain the target posture was considered the trial score. The target postural tolerance was 5°, which was determined by the repetitive pilot testing of the trials. In our previous study [43], both the passive SPINDLE ADLs without tremor and the natural ADLs had a normative standard variation of around 2°. If the participant moves into the target faster (accomplishing the ADL posture faster), the participant will have a higher score. Additionally, the participant will receive a higher score if they are capable of maintaining the hand posture within the target for an extended duration. A trial capture began when the participant aligned their arm on the natural object or SPINDLE handle and was ready to move. From this instance until the next twenty-second period was considered a trial [50]. The details of the task protocol can be found in Appendix A.

3) Sensor Location: Reflective markers were attached to the following positions to calculate the ZYX Euler angles of the shoulder, elbow, and wrist: seventh cervical vertebrae, eighth thoracic vertebrae, sternum for the trunk, acromion, deltoid, lateral epicondyle of the humerus, medial epicondyle of the humerus, radial styloid, ulnar styloid, third metacarpal bone, mid-humerus, mid-radial, and mid-ulnar. sEMG sensors were attached to the following muscles: flexor digitorum superficialis, flexor carpi radialis, extensor digitorum, flexor digitorum profundus, brachioradialis, triceps longhead, bicep brachii, posterior deltoid, middle deltoid, anterior deltoid, upper trapezius.

D. Data Analysis

All data were recorded for each specific trial. The reflective marker data was acquired at 100 Hz, and the sEMG data was recorded at 2000 Hz. ROM and sEMG activation data were quantified while performing natural and SPINDLE ADLs. The reflective marker data was filtered with a low pass filter with a cutoff frequency of 10 Hz. For each trial, the ROM of upper limb joints was obtained by calculating the difference between the maximum and minimum of the joint movements within a trial. The sEMG signals were recorded and computed for each trial and then averaged among the respective ADL trials. The sEMG post-processing is performed as follows.

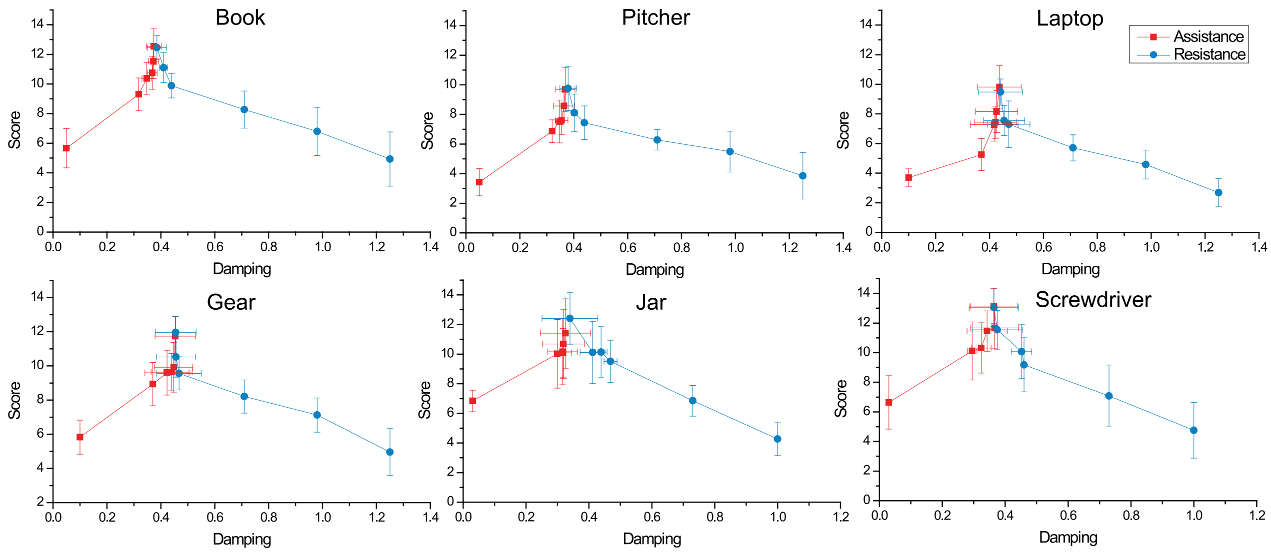

Fig. 7. Nine participants' iterative average score and damping results when starting at lowest damping (Red) and highest damping (Blue).

After filtering, enveloping, and smoothing, the maximum and minimum value was computed for each ADL task (i.e., book flipping). Maximum and minimum values were used in sEMG scaling using Eq. (3). $i = 1, \ldots, 6$ indicates the order of book, pitcher, laptop, gear, jar, and screwdriver tasks. $j = 1, \ldots, 11$ indicates the order of digitorum superficials, flexor carpiradialis, extensor digitorum, flexor digitorum, brachioradialis, triceps long-head, biceps, posterior deltoid, middle deltoid, anterior deltoid, and upper trapezius. The sEMG was then normalized across all ADL tasks to compare the sEMG between the different modalities (low, optimal, high).

$$\frac{value - min_{i,j}}{max_{i,j} - min_{i,j}} \tag{3}$$

E. Statistical Analysis

The primary measures for the natural or simulated ADL tasks were ROM and muscle activation using surface electromyography (sEMG). The comparison in ROM between the natural and SPINDLE tasks was tested with a pairwise t-test using Bonferroni correction for seven comparisons between different movements within each task ($\alpha = 0.007$). The comparison in ROM and sEMG between different dampings was also investigated with rANOVA and post-hoc test. As post-hoc test, Bonferroni-Holm correction was performed to identify the significant pairs [51]. Cohen's d is computed for the effect size [52]. $d < 0.5$ is considered as small effect, $0.5 \leqq d < 0.8$ is considered as medium effect, and $d \geqq 0.8$ is considered as large effect. All statistical analyses were performed using SPSS 27 (IBM Corp., Armonk, N.Y., USA) with $\alpha = 0.05$.

III. Results

A. Finding Optimal Damping Proportional to the Score

The process to find the optimal damping for each task is illustrated in Fig. 7. It displays the average and standard deviation of the results for each iteration. The results demonstrate that all SPINDLE ADL tasks displayed a converging pattern towards their respective optimal damping levels. For the book task, the optimal damping level was 0.38 ± 0.04 Ns/m, and the corresponding score was 12.5 ± 1.2 s. The resulting ideal damping level for the pitcher task was 0.36 ± 0.03 Ns/m for a score of 9.7 ± 1.5 s. In the laptop task, both modes converged to a damping level of 0.44 ± 0.08 Ns/m and an identified score of 9.8 ± 1.4 s. The optimal damping level for gear task was 0.45 ± 0.07 Ns/m, and the best performance score was around 11.9 ± 1.15 s. In Jar task, the best damping value was roughly 0.33 ± 0.088 Ns/m, with a score of 12.4 ± 1.7 s. The representative, effective damping level and score for the screw task were 0.36 ± 0.07 Ns/m and 13.1 ± 1.18 s.

B. Kinematic Comparison Between Natural and SPINDLE ADLs

The natural and SPINDLE ADLs were compared to validate whether SPINDLE ADLs can train participants with a similar ROM as the natural ADLs. The ROM showed similar trends between natural and optimal SPINDLE trials among all ADL tasks, illustrated in Fig. 8. All upper limb joints did not show significant differences in ROM when comparing the real-world and SPINDLE ADL tasks. The book opening and screwdriver tasks showed increasing trends in the SPINDLE task for wrist pronation/supination. In addition, the SPINDLE pitcher pouring task showed a decreasing trend in radial-ulnar deviation of the wrist. It should be noted that statistical analysis shows that all upper limb joints ROM had no significant difference while performing natural and SPINDLE ADL tasks with optimal damping validating the use of SPINDLE to emulate realistic ADLs.

C. Different Damping Levels During ADLs

1) Range of Motion With Different Damping Levels: In this experiment, despite utilizing different damping parameters, we anticipated to observe similar ROMs of the upper limb

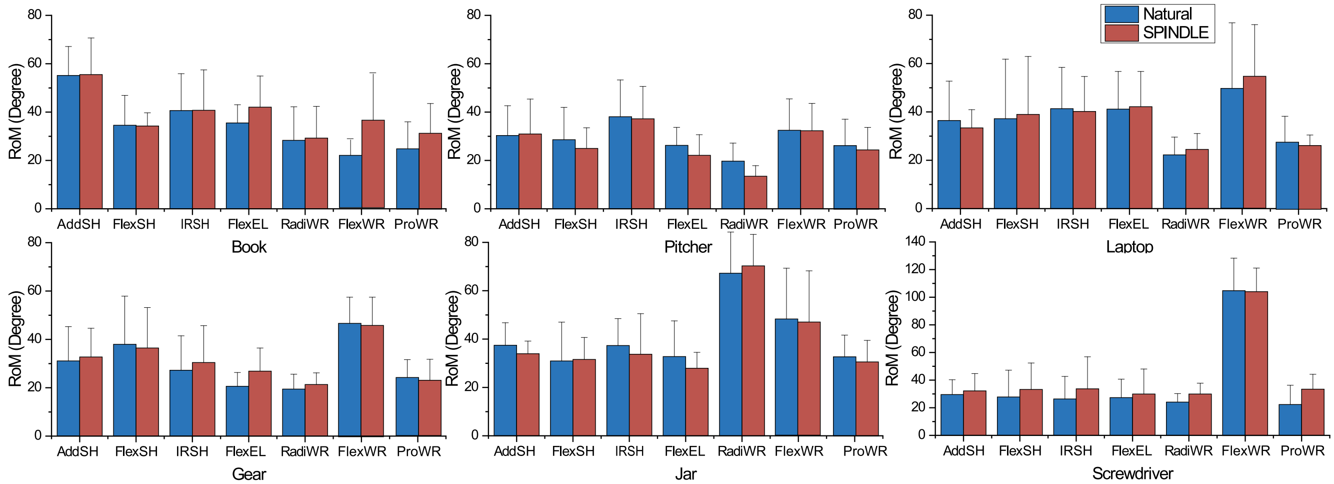

Fig. 8. Range of motion of the shoulder, elbow, and wrist during natural and SPINDLE ADL tasks. AddSH: adduction/abduction shoulder, FlexSH: flexion/extension shoulder, IRSH: internal/external rotation, FlexEL: flexion/extension elbow, RadWR: radial/ulnar-deviation wrist, FlexWR: flexion/extension wrist, and ProWR: pronation/supination wrist.

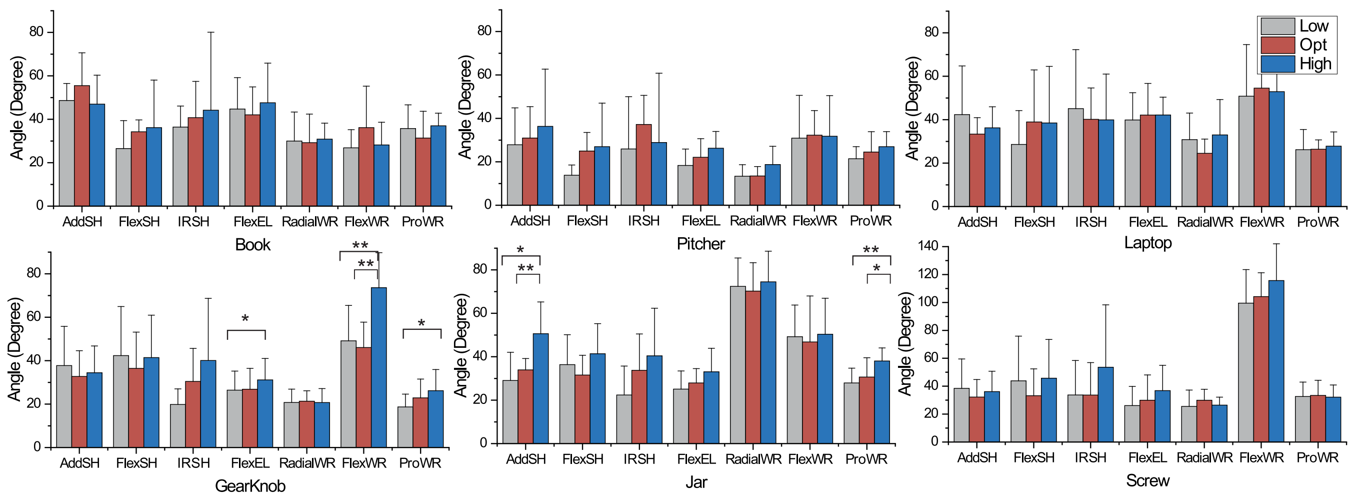

Fig. 9. ROM of shoulder, elbow, and wrist during low, medium (optimal), high damping six ADL tasks with SPINDLE. The optimal damping was identified by the algorithm in Fig. 6. AddSH: adduction/abduction shoulder, FlexSH: flexion/extension shoulder, IRSH: internal/external rotation, FlexEL: flexion/extension elbow, RadWR: radial/ulnar-deviation wrist, FlexWR: flexion/extension wrist, and ProWR: pronation/supination wrist. * indicates $p < 0.05$ and ** indicates $p < 0.01$.

because participants would perform the same ADL task (i.e., identical task-space movements). The trend of ROM between low, optimal, and high damping indicates that most of the joint movements show no significant difference ($p > 0.05$), as shown in Fig. 9. For the book, pitcher, laptop, and screw tasks, no significant changes were detected in any joints. The gear task indicates that ROM of wrist flexion/extension in high damping was significantly higher than in low and optimal damping trials (both pairs $p < 0.001$, $d > 2$). A similar pattern was observed for wrist pronation/supination, except that the only significant increase was detected for high damping compared to low damping ($p = 0.035$, $d = 1.08$)). Similarly, high damping for elbow flexion/extension showed increased ROM compared to low damping ($p = 0.046$, $d = 1.03$). Based on the results, it is observed that subjects have displayed greater joint ROM when they experience higher resistance during gear tasks. The result of rANOVA of the jar task showed a significant increase in higher damping compared to low & optimal damping for shoulder adduction/abduction, shoulder rotation, and wrist pronation/supination. Significant pairs from post-hoc tests were observed for low-high damping & optimal-high damping cases ($p = 0.02$, $d = 1.22$ & $p = 0.005$, $d = 1.46$ for shoulder rotation and $p = 0.001$, $d = 1.92$ & $p = 0.044$, $d = 0.94$ for wrist pronation/supination). Although similar levels of the ROM are desired among all damping levels, for the sake of training, increased ROM in high damping would help in training targeted or slightly greater ROMs for most ADLs.

2) Surface Electromyography With Different Damping Levels: sEMG is used to investigate whether optimal damping could aid individuals with emulated tremor in carrying out ADL tasks and reducing muscle effort. Fig. 10 displays the comparison of sEMG levels for six distinct ADL tasks during low, optimal, and high damping. The SPINDLE book task showed a significant decrease in muscle activation during optimal damping for extensor digitorum (ED), brachioradialis (BRA), and anterior deltoid (ADE) muscles. The ED showed smaller

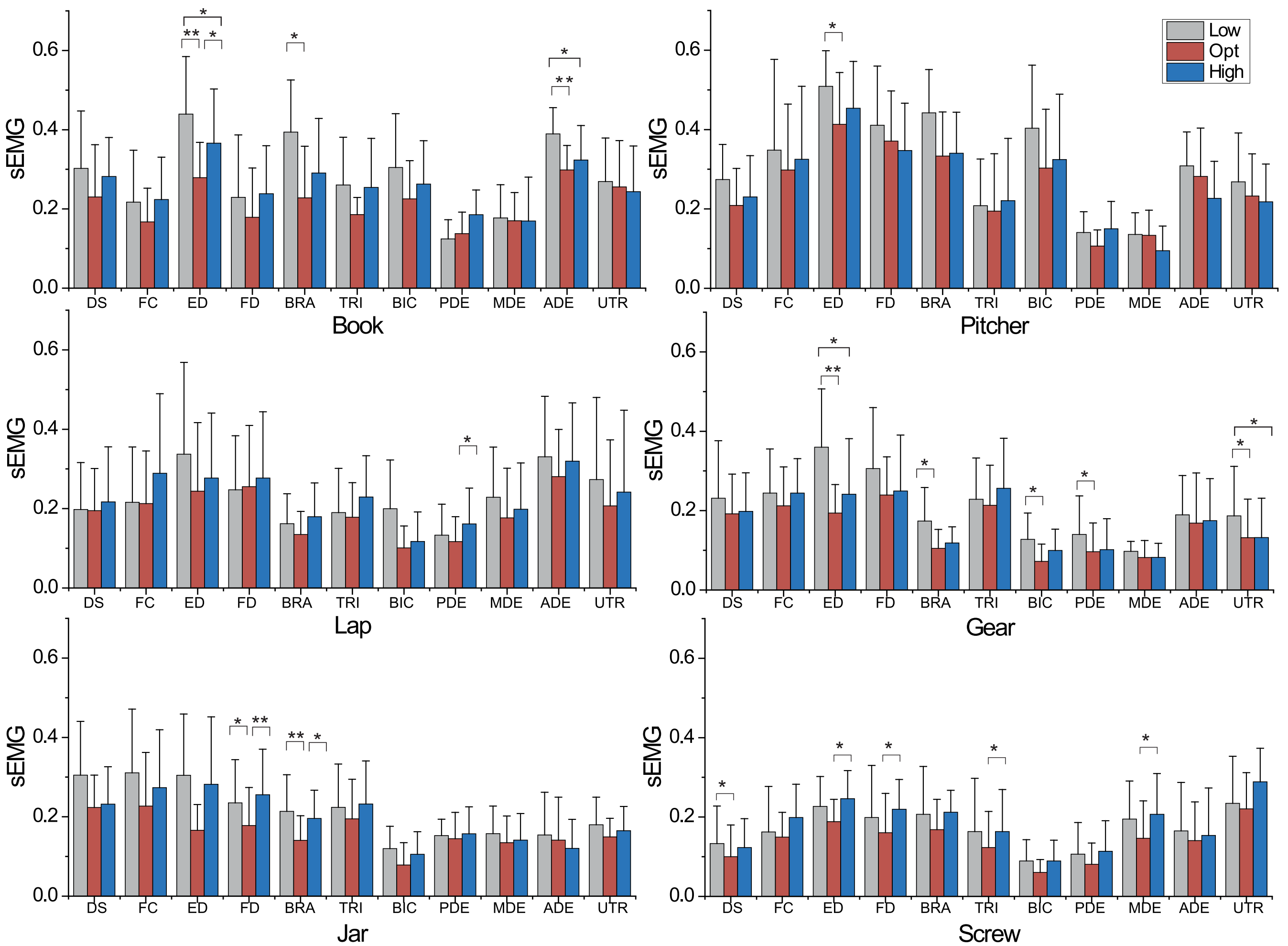

Fig. 10. Surface electromyography during low, optimal, high damping ADL tasks with SPINDLE. sEMG includes Digitorum Superficials (DS), Flexor Carpiradialis (FC), Extensor Digitorum (ED), Flexor Digitorum (FD), Brachioradialis (BRA), Triceps long-head (TRI), Biceps (BIC), Posterior Deltoid (PDE), Middle Deltoid (MDE), Anterior Deltoid (ADE), and Upper Trapezius(UTR). * indicates $p < 0.05$ and ** indicates $p < 0.01$.

sEMG activation in optimal damping, which is indicated as low-optimal ($p = 0.003$, $d = 1.67$), optimal-high ($p = 0.030$, $d = 0.88$), and low-high ($p = 0.039$, $d = 0.98$) pairs. The BRA also exhibits decreased activation in optimal damping (low-optimal: $p = 0.031$, $d = 1.11$). The ADE showed decreased activation in optimal damping, indicated by low-optimal damping ($p = 0.007$, $d = 1.46$) and low-high damping ($p = 0.022$, $d = 1.09$) pairs. This showed that optimal damping in SPINDLE provided proper assistance to stabilize the emulated tremor of participants and reduce the user's effort to perform the task.

In the pitcher and laptop tasks, similar trends were observed, but the advantage of optimal damping was not significant, except for the ED during pitcher task (low-optimal: $p = 0.040, d = 1.06$) and posterior deltoid (PDE) during laptop task (optimal-high: $p = 0.018, d = 1.24$). The gear task showed a trend that higher muscle activation was observed during low damping than optimal & high damping. This means that this task requires extra effort to stabilize the joint during low damping. High muscle activation was not observed during high damping because the gear handle enabled users to easily provide the force that is required to move against the resistance. The ED showed a significant increase in low damping compared to optimal ($p = 0.003$, $d = 1.64$) and high damping ($p = 0.044$, $d = 0.95$). The BRA showed a significant increase in low damping compared to optimal ($p = 0.012$, $d = 1.33$). Similarly, the biceps (BIC) and shoulder extensor muscle (PDE) showed a significant increase in low damping compared to optimal damping ($p = 0.038, d = 1.07$ & $p = 0.023$, $d = 1.17$ respectively). Upper trapezius muscles showed a significant increase for low damping as shown in low-optimal ($p = 0.016$, $d = 1.27$) and low-high ($p = 0.025, d = 1.074$) damping pairs.

The jar task showed significant decrease in optimal damping compared to low and high damping for wrist/elbow flexor and extensor muscles. Significant decrease in flexor digitorum(FD) was observed for optimal damping (low-optimal damping ($p = 0.016, d = 1.17$) and optimal-high damping ($p = 0.006$, $d = 1.50$) pairs). BRA was also engaged in this jar cap turning task, which showed a similar trend for low-optimal ($p = 0.006$, $d = 1.50$) and high-optimal pairs ($p = 0.011$, $d = 1.25$). The participants leveraged the optimal resistance when performing the jar task with their wrist and elbow joints.

All muscles during the screw task showed that optimal damping was lower than high or low damping. Compared to optimal damping, Digitorum superficials (DS) showed significant increase in low damping ($p = 0.019$, $d = 1.21$), the ED and FD showed significant increase in high damping ($p = 0.042$, $d = 1.04$ & $p = 0.012$, $d = 1.34$ respectively). The triceps (TRI) and middle deltoid (MDE) muscles also showed a significant increase in high damping ($p = 0.036$, $d = 1.09$ & $p = 0.019$, $d = 1.22$) to maintain the height of screwdriver during the task. The screw task characteristics necessitated the forearm to be aligned with the upper arm in the longitudinal axis, and the task was performed by pure axial rotational movements. In order to achieve pure rotation, other joint axes were locked by activating both agonist and antagonist muscles. Participants utilized SPINDLE's optimal damping for most of the joints to generate pure axial rotation for the screw task.

IV. Discussion

The present study showed that the SPINDLE-based ADLs and physical tasks are equivalent in joint mobility, demonstrating its potential as an evaluation tool for quantifying ADL performance. This comparison indicates that SPINDLE has a high potential for transferability of training to natural ADLs. The intended ADL activities include reaching and precise posture matching, allowing participants to practice coordinating proximal and distal joint movements. In addition, we provided a method for determining the controller's optimal virtual damping based on user's task performance.

For resistance-based training, optimal damping will be computed to tailor the resistance level for individuals with unknown tremors. To train participants to activate strong agonist muscles for generating smooth voluntary motion and isolating agonist & antagonist muscles, it is necessary to train the participant with large resistance intensively. Resistance also assists in tremor attenuation. However, excessive resistance will make it difficult for participants to move their limbs while conducting ADL tasks. Thus, optimal damping is required for efficient resistive training, and it will serve as the starting point of the resistive training of ET patients. The present study shows that the optimal damping differed for each individual when participants performed different ADLs. For instance, the highest damping was observed in the gear task because the power grasp (cylindrical) of the gear task requires the strongest grip and the pulling-pushing motion recruits large flexion-extension muscles to handle the large resistance of the system [53]. In contrast, the lowest optimal damping level was identified in the jar task. This is because the jar task requires a sphere grasp, which is weaker and the cap rotation requires arm joint twisting, resulting in a lower output torque than pulling-pushing motion. The plane of the rotation of the handle also affects the optimal damping because hand posture changes the grip strength and the manipulation ability [54], [55].

Along with tremor suppression through viscous damping, combining the SPINDLE system with an adaptive resistive training technique provides significant advantages for enhancing neurophysiological factors such as strength, muscle activation, motor control, coordination, and neuroplasticity. SPINDLE's ability to tailor the resistance levels precisely facilitates distinct muscle activation. This approach may potentially improve neuroplasticity by stimulating some parts of the user brain (such as ipsilateral cerebellum or contralateral sensorimotor cortex or contralateral thalamus) based on the activity. ADL-based resistive robotic training may promote the reformation of neural connections [56]. Furthermore, this may also potentially promote optimal muscle fiber recruitment and strength gains. The optimal resistance and visual feedback during training can enhance the user's dexterity and hand-eye coordination skills. Which ultimately may aid in the refinement of movement patterns, the correction of motor control impairments, and the progress of coordination, with the potential for transfer to functional ADLs [57]. Finally, incorporating varied difficulty levels enhances user's motivation, as it mitigates monotony and frustration often associated with repetitive therapy and can optimize neuroplastic changes [45].

Typically, conducting ADL requires a unique combination of motion, grasp pattern, and grip strength [58]. It is shown by distinct ROM and sEMG activities of the upper limb during six ADL tasks. For example, both book and pitcher tasks occur in the coronal plane, but the book task needed a larger side-by-side motion of the hand-generated by shoulder adduction/abduction (Fig. 8). The book task also demanded a parallel expended grasp of the end-effector from the side. In contrast, the pitcher task required grasping the object from an elevated height with a power grip. Book and laptop tasks share the same grip type, but their grip posture is different, resulting in different upper limb movements. The laptop task demanded an even ROM in all three shoulder rotations and flexion/extension of the wrist, which is different from the motion of the book task. To cover as many ADLs as feasible, SPINDLE encompasses a variety of planes of rotation, grasp types, and motions such that the participant can practice integration of proximal joint with distal joint training, which may enhance functional gains needed for ADLs [59], [60]. The combination of diverse tasks will allow users to acquire a broader repertoire of motor skills, facilitating skill generalization across different activities. Cross-training enhances motor learning and forces the modification of movement strategies by progressively exposing users to different ADLs of rising complexity.

SPINDLE presented its effectiveness in evaluating and training the natural ADLs by demonstrating a comparable movement to earlier studies that examined the upper limb ROM during ADLs [61], [62]. These studies show a similar ROM of shoulder, elbow, and wrist for various tasks such as door knob rotation, pouring pitcher task, etc., when compared with SPINDLE ADLs. In a few robotic studies, the ROM while executing ADLs using robots has also been investigated [38], [41]. As a representative exoskeleton-type rehabilitation system, ARMin III [38] measured the upper limb joint ROM of the participant during three virtual ADLs (cooking, cleaning, and using a ticket machine). The ROM measured in this study was similar to ROM during the SPINDLE task (see Appendix C Table III). Another end-effector-based single rotational device, ADAPT [41], was also developed for practicing and evaluating ADLs. It can rotate the end-effector up to 130° with a maximum torque of 2.5 N. SPINDLE has a similar yaw-axis 126° rotation capacity and max torque of 2.6 Nm. ADAPT was designed to vary the stiffness of the end-effector to mimic the diverse stiffness of ADL objects. Similar to SPINDLE, ADAPT can also provide adaptable ADL-specific training depending on the movement time required to complete ADL activities. Unlike ADAPT, SPINDLE has the capability to rotate the end-effector in all three dimensions with a range of motion and torque similar to a single rotation of ADAPT.

Most participants reported that they like the interactive VR gamification strategy for increasing their motivation and self-efficacy to enhance their task score, which motivated them to consistently use their upper limbs for extended periods. In addition to the hardware capabilities of SPINDLE, the user's feedback was quantified by asking them questions on 'How they feel about the system' or 'What did you like about the system.' They notably stated that SPINDLE gave them an intuitive understanding of their hand movements and guided them to do full-fledged upper limb movement while improving their hand-eye coordination. Several subjects were intrigued by SPINDLE's ability to provide real-time position feedback on the object's state awareness (i.e., object position feedback in 3-D space), which aided users in completing precise movements across all ADLs.

The current limitation of the study is as follows. First, we only investigated one-dimensional rotational tasks as a pilot study. The system can perform complex three-dimensional rotations. Thus, ADL tasks requiring dexterous three-dimensional rotations, such as mimicking buttoning, need further investigation. Second, the study shows only one pilot session, which does not show how the optimal points change over time. As the training progresses, the participants may choose a different optimal resistance of the system due to finding new movement strategies or learning effects.

Last, the current study focuses on healthy participants with simulated tremors only. The participant feedback of individuals with essential tremors is important to tailor practical therapy in the future. For the next iteration of this study, individuals with tremors and muscle weakness will be recruited and trained with this system. People with tremor will be trained with resist-as-needed SPINDLE training to promote the separation of agonist and antagonist muscles to achieve improved voluntary motion. Previously, resistive training was effective in correcting muscle activation that was coupled by unwanted co-activation of muscles [63]. Repeated functional movement with resistance will let the participant practice intensively to activate the agonist muscle. We believe the ability to separate agonist and antagonist muscles will lead to a larger ROMs by reducing the unwanted motion generated from the antagonist muscle. In the future, we will measure the sEMG to show whether the activation of antagonist muscle is decreased in ET patients.

In addition to the resist-as-needed training strategy, other participant-centered analysis will be performed to analyze the detailed ADL performance and individuals' iterative upper limb motor enhancements. Clinical standard metrics such as Fugl-Meyer, Barthel Index, Functional Independence Measure, and Nottingham extended activities of daily living will also be analyzed. In the future, we will employ reinforcement learning methods to develop data-centric AI controllers for optimal autonomous training using task-space movements, damping, and score data.

The broad goal of the present work is to demonstrate the feasibility of utilizing SPINDLE to guide and train individuals with tremors and strengthen their upper limbs. The proposed system can train various ADLs requiring 3-dimensional rotational movements by providing optimal resistance and visual feedback. Experimental results have shown SPINDLE's potential to mimic natural ADLs and provide immediate performance feedback. After each trial, the resulting score indicates the ADL-specific performance; built on task duration, reach, and dexterity skills. Immediate feedback in terms of the score improved users' motivation and self-efficacy. The experiment data of most participants implied that the game-based environment sustained their interest in training longer. Furthermore, visualization of the target posture and direction enhanced the ADL training performance regarding adequate joint movements. We envision SPINDLE can be used as a novel, compact tool that reflects ADL training, with the potential carryover of training effects to individuals' daily living and improve their quality of life.

V. Conclusion

This study demonstrates that the movements of the upper limb during real-life and SPINDLE ADLs are comparable. By landscaping the resistance, the optimal resistance for each participant can be identified when performing a specific ADL task. Participants can enhance their upper limb strength and dexterity by practicing emulated ADLs of SPINDLE. SPINDLE can provide a broad range of mobility in three-dimensional task space, which can facilitate a greater diversity of ADL tasks. Integrating SPINDLE with the virtual ADL gaming environment will enhance participant performance in dexterous task space manipulation and sustain their interest in training for extended periods. We envision this compact rehabilitation system can be used as a home device and provide personalized resistive therapy for patients with tremors.

Appendix A
Detailed ADL Task Description

The participant repeats below protocol seven times to perform the task at various intensity levels with intermittent breaks.

■ Book: The book task is performed with a thin plate as an interface, which demands a parallel expended grasp of the end-effector from the side. Flipping the book is achieved by the rotation occurred in the medial-lateral direction. The grip of the book task demands a larger side-by-side motion of the hand generated by shoulder adduction/abduction. Before starting, the participant grabs the book cover by the marking on it. After hearing two metronome beats, the participant flips the book cover 180 degrees. The participant holds the book cover throughout this motion and then flips the book back after hearing two metronome beats. Participant repeats this for two more times. For the SPINDLE book, the participant performs a similar movement.

■ Pitcher: The pitcher task required grasping the object from a higher height than book task with a power grip. Even though book and pitcher tasks shared the same axis of rotation, participants relied more on shoulder rotations to complete the pitcher task than the book task. Participant holds the handle before the task starts. After the participant hearing two metronome beats, he/she performs the pouring operation and hold. The participant repeats these two more times. For the SPINDLE pitcher, the participant performs a similar movement.

■ Laptop: The laptop task had a similar end-effector interface as the book task, which was a thin plate. Thus, book and laptop tasks share the same grip type, but their grip posture and rotational axis differ, resulting in different upper limb movements. The laptop task rotation occurred in the anterior-posterior direction. To open the laptop, flexion of the shoulder was dominant, which was presented in activation of the posterior deltoid muscle. The task is started when the participant's hand aligns on the laptop's transverse plane. The participant hears two metronome beats and opens it to reach its end and hold. After that, the participant resets to the base position and waits for a beat. The participant repeats the task two more times. For the SPINDLE laptop, the participant performs similar movements.

■ Gear: The power grasp (cylindrical) of the gear task is the most strongest grip among the six tasks. Because pulling-pushing motion is required for the gear task, both digitorum were activated, as participants tend to recruit their forearm muscle groups to move the handle back and forth by activating the flexor and extensor of the wrist. The task is started when the hand aligns on the gear knob, and two beats have occurred. The participant moves the knob forward (away from the body) once. Afterward, the participant returns to the home position and waits for one beat. After the hand aligns on the gear knob and two beats have occurred, the participant repeatedly moves the knob backward (towards the body). The participant repeats this task two more times. The participant holds the SPINDLE gear handle like a natural task for forward and backward movements.

■ Screwdriver: The screwdriver task started with an inverted power grasp of the screwdriver. The screw task characteristics necessitated the forearm to be aligned with the upper arm in the longitudinal axis, and the task was performed by pure axial rotational movements. The screwdriver task relied on wrist flexion/extension to achieve the axial rotation. Before the task, the participant lines the screwdriver up to the center of the screw to prepare a twisting motion. After two beats have occurred, the participant tightens (clockwise rotation) the screw once. After the screwdriver is aligned and two beats have occurred, the participant loosens (counterclockwise rotation) the screw once. The participant repeats the clockwise and counterclockwise rotation two more times. For the SPINDLE screw, the participant holds the screwdriver handle, like the natural task of twisting the screw, in a VR environment. The rest of the procedure is identical to the natural screw task and repeats six times.

■ Jar: The jar cap task requires a sphere grasp of the cap, and the cap is turned in clock and counter-clock directions. The extensor and flexion digitorums were highly activated because this task required a wide steady grasp of the cap of the jar and demanded radial-ulnar deviation of the wrist. After the hand aligns on the jar cap and two beats have occurred, the participant closes (clockwise rotation) the jar cap once. After that, the participant returns to the home position and waits for one beat. After the hand is aligned on the jar cap and two beats have occurred, the participant opens (clockwise rotation) the jar cap for one time. After that participant returns to the home position and waits for one beat. The participant repeats the task two more times. For the SPINDLE jar, similar to the natural jar, the participant performs the clockwise rotation (closing the jar) and counterclockwise (opening the jar) rotation one time each.

TABLE I
TASKSPACE ROM AND PEAK FORCE OF SPINDLE ADLS

Task	ROM	Peak Torque
Book	162 deg	0.32 Nm
Pitcher	72 deg	0.26 Nm
Laptop	81 deg	0.28 Nm
Gear	108 deg	0.26 Nm
Jar	120 deg	0.12 Nm
Screwdriver	90 deg	0.15 Nm

APPENDIX B
TASK-SPACE ROM AND PEAK FORCE

Table I displays the maximum SPINDLE ROM and respective average peak torques quantified among all subjects. Among ADLs, book & pitcher tasks were performed in the medial-lateral plane, and laptop & gear tasks were performed in the anterior-posterior plane. Both rotational ADLs: jar and screwdriver tasks were performed on the longitudinal axis. Book task displays the highest task space ROM; in contrast, the pitcher task exhibited the lowest ROM. The book task displayed the highest peak torque, and the pitcher task showed a low peak torque. Rotational task on axial axis: jar task displayed higher ROM and low peak torque. In contrast, the screwdriver displayed comparably low ROM and higher peak torque.

APPENDIX C
ROM OF NATURAL AND SPINDLE TASKS

Table II presents the average and standard deviation of joint ROM compared to the natural and SPINDLE-emulated ADLs. It illustrates that SPINDLE can emulate comparably similar or greater joint ROMs. Except for shoulder flexion/extension, which is limited to 65 degrees, and elbow flexion/extension, which is limited to 63 degrees. Results of this study provide evidence that the utilization of SPINDLE, coupled with a defined ROM and the resist-as-needed methodology, holds promise for simulating natural movements and facilitating improvements in upper limb strength and dexterity skills

TABLE II
ROM COMPARISON WITH THE NATURAL ADLS

Factors	SPINDLE	Natural [61], [62]
Shoulder Add/Abdu	59 ± 13 deg	60 deg
Shoulder Flex/Ext	45 ± 20 deg	100 deg
Shoulder Pro/Sup	47 ± 33 deg	90 deg
Elbow Flex/Ext	49 ± 14 deg	80 deg
Wrist Radial/Ulnar	72 ± 13 deg	60 deg
Wrist Flex/Ext	110 ± 20 deg	80 deg
Wrist Pro/Sup	39 ± 10 deg	45 deg

TABLE III
ADL-SPECIFIC ROM COMPARISON WITH ARMIN III [38]

Factors	SPINDLE	ARMin III [38]
Shoulder Add/Abdu	59 ± 13 deg	100 deg
Shoulder Flex/Ext	45 ± 20 deg	85 deg
Shoulder Pro/Sup	47 ± 33 deg	90 deg
Elbow Flex/Ext	49 ± 14 deg	120 deg
Wrist Radial/Ulnar	72 ± 13 deg	0 deg
Wrist Flex/Ext	110 ± 20 deg	80 deg
Wrist Pro/Sup	39 ± 10 deg	45 deg

through personalized resistance treatment. These findings highlight the potential efficacy of the SPINDLE system as a valuable tool in the realm of rehabilitation for enhancing motor abilities and functional performance in individuals.

APPENDIX D
SPINDLE VS OTHER ROBOTIC ADL TASKS

Table III compares the average ROM of the SPINDLE and Armin III for each upper limb joint during representative ADLs.

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