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# Zesty Exercise System for Therapeutic Engagement (ZEST-E)

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An abstract of
a thesis submitted to the Faculty of Emory College of Arts and Sciences
of Emory University in partial fulfillment
of the requirements of the degree of
Bachelor of Science with Honors

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# Abstract

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***Importance:*** Parkinson’s disease is a common neurodegenerative disease that causes various symptoms such as bradykinesia, a resting tremor, and postural reflex deficits (Jankovic, 2008). Physical therapy can address many of the symptoms associated with Parkinson’s disease, but people with Parkinson’s disease frequently fail to achieve the full benefits of exercise sessions due to the limited time therapists can dedicate to individual patients (Clarke et al., 2016). Home robotics may be a potential solution to increase the time individuals with Parkinson’s disease are able to engage with therapeutic exercises, and a home robot programmed to deliver physical therapy activities could make frequent and consistent exercise more accessible.

***Objective:*** To determine 1) if a robot-led exercise system can lead people with Parkinson's disease through a wide range of motion at different joints and 2) if people with Parkinson's disease are able to execute the exercises as instructed by the robot.

***Design/Setting:*** Pilot interventional study.

***Participants:*** 11 older adults (68.2 ± 5.9 years old), four males and seven females, with a Parkinson’s disease diagnosis provided by a Movement Disorders specialist.

***Main Outcome and Measure:*** Range of motion and physical therapist survey responses.

***Results:*** Participants were able to move through a large range of motion that targeted hip flexion, knee extension, knee flexion, ankle plantarflexion, and torso twist. Participants had higher rates of adherence to the verbal directions than the video instructions. The most common form errors were improper form between repetitions, and the most common hypothesized cause of form errors was misunderstanding instructions.

***Conclusion and Relevance:*** Participants achieved a maximum range of motion that is largely consistent with the literature’s comparative standard range of motion values. Instruction adherence was a challenge for users, but this finding may be due to the study design rather than the complexity of the exercises or the device.

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# Zesty Exercise System for Therapeutic Engagement (ZEST-E)

**By Arielle Wallenstein**

**Wesley Woods Health Center, Emory University School of Medicine, the Atlanta VA Medical Center, and Georgia Institute of Technology**

**Honors Thesis**

## Hypothesis

This study was designed to answer two primary research questions. 1) Can a robot-led exercise system lead people with Parkinson's disease (PD) through a wide range of motion (ROM) at different joints? We hypothesized that ZEST-E's exercise regimen would guide people with PD through a large ROM, and this ROM will target hip flexion, knee extension, knee flexion, ankle plantarflexion, and torso twist. 2) Are people with PD able to execute the exercises as instructed by the robot? We hypothesized that participants would be able to complete the physical therapy (PT) exercises as intended after listening to ZEST-E's verbal directions and watching the system's associated instructional videos that are displayed before the participant completes each exercise.

## Introduction

### Parkinson's Disease:

*History and Background*

PD is the most prevalent motor disorder and the second most prevalent neurodegenerative condition targeting the central nervous system, affecting 1% of those above the age of 60 and 4% of people 80 years and older (Gwinn, 2013; Tysnes & Storstein, 2017). First documented in 1817 by English surgeon James Parkinson in a publication titled “An Essay on the Shaking Palsy,” it was not his patients that led Dr. Parkinson to report on this novel condition, but instead, it was the posture and gait of three older men he observed in the streets of Hoxton, London. While Dr. Parkinson himself referred to the disease as “paralysis agitans,” the condition was renamed “malalie de Parkinson” (Parkinson’s disease) by French neurologist Jean-Martin Charcot in 1872. Dr. Charcot and his students broadened the current understanding of the condition, rendering the original nomenclature misleading, given that not all patients experience weakness and tremors (Beidler, 2020; Goetz, 2011).

### *Pathology*

Although PD is categorized as a neurodegenerative motor condition, patients tend to present with non-motor symptoms before displaying the cardinal motor deficits of PD. Such non-motor impairments are reported to arise from extranigral pathological changes involving the lower brainstem, olfactory bulb and tracts, and the peripheral autonomic nervous system (Tolosa et al., 2021). Several clinical studies have found that individuals with PD frequently report an impaired sense of smell years before they experience somatosensory and motor impairments, and these findings are consistent with results from a 2003 study that discovered evidence of early brain lesions within olfactory structures (Braak et al., 2003). Regarding motor symptoms, progressive loss of dopaminergic neurons from the pars compacta subnuclei of the substantia nigra is credited as the core pathologic feature of PD. However, while this substantia nigra loss is frequently hypothesized to be the root cause of the motor symptoms that characterize PD, there are actually three constituent regions that undergo sequential deterioration. First is the gain setting system, comprised of three nuclei in the lower brain stem (the caudal raphe nuclei, the coeruleus-subcoeruleus complex, and the gigantocellular reticular nucleus), and this is followed by destruction of the substantia nigra and later by nuclei located in the thalamus and other prefrontal association fields (Braak et al., 2003).

### *Symptoms*

As summarized in Figure 1, the trajectory of PD progression can be divided into two subcategories: the prediagnostic phase, which may be further differentiated into a preclinical and a prodromal stage, and the manifest PD phase, consisting of the early and late stages. The point of diagnosis generally falls at the transition between the prediagnostic and manifest phases. Prior to the display of signs and symptoms of PD, an individual is considered to have preclinical PD. It is hypothesized that PD-specific pathology is already occurring years before diagnosis and that this process antedates the onset of symptoms. Once early symptom exposure occurs, patients leave the preclinical stage and transition to prodromal PD. Entrance into this period typically predates diagnosis by 15 years and is characterized by a plethora of non-motor disturbances. Constipation, loss of smell, and rapid eye movement-sleep behavior disorder are the most common early symptoms that patients experience, but anxiety, color vision impairment, depression, dysexecutive syndrome, hypotension, and sexual dysfunction have also been reported. Additionally, while what distinguishes the prodromal stage of PD is a set of unspecific non-motor symptoms, mild motor impairments such as a decreased arm swing while walking, decreased facial mobility, loss of finger dexterity, mildly stooped posture, and voice changes can arise concurrently (Tolosa et al., 2021).

Both the early stage and the late stage of manifest PD are defined by disparate motor and non-motor symptoms. In the early stage of PD, patients generally display four cardinal motor symptoms: bradykinesia, gait alterations, rigidity, and tremor. With bradykinesia, individuals experience slowness of spontaneous movement and reduced speed and amplitude of voluntary movements. Gait alterations may appear as a decreased arm swing, dragging of one leg, and a hunched posture. Rigidity is the term used to describe increased muscle tone, and tremor is typically observed in the chin, jaw, limbs, and lips. These motor symptoms tend to persist into the later stage and are accompanied by freezing of gait and postural alterations (Tolosa et al., 2021).

In early stage PD, patients may also endure autonomic dysfunction (constipation, delayed gastric emptying, erectile dysfunction, heat intolerance, incontinence, orthostatic hypotension, and urinary urgency); loss of smell (hyposomnia); mild cognitive impairment; neuropsychiatric features (anxiety, apathy, and depression); sleep disorders (akathisia, excessive daytime sleepiness, insomnia, parasomnia, periodic limb movements, and restless leg syndrome); and somatosensory symptoms (burning sensations, pain, and paraesthesias) (Tolosa et al., 2021). Similar to the motor symptoms, these concerns tend to persist, often worsening, as a patient's condition advances. Mild cognitive impairment can progress to dementia, and studies have shown that there is a >75% prevalence of dementia in individuals who have had PD for ten years or longer (Erkkinen et al., 2018). Such cognitive decline may also be associated with hallucinations, psychosis, and a poor ability to dual task, defined as the ability to pay attention to two tasks at once, such as walking and counting (Plotnik et al., 2011; Tolosa et al., 2021).

### *Diagnosis*

Diagnosing PD is challenging because symptoms can be difficult to distinguish from other neurodegenerative diseases, such as multiple system atrophy, cortical basal degeneration or parasupranuclearn palsy, or from normal aging, and this struggle is further complicated by the fact that there is no definitive biomarker or blood test for PD. As a result, a proper diagnosis may not be received until years or decades after the initial onset of symptoms. Laboratory tests and imaging studies are frequently utilized to rule out other medical conditions, but a diagnosis of PD is delivered based on the clinical symptoms with which a patient presents. Additionally, though PD is hypothesized to have developed sporadically in most patients, there is also a genetic component to the etiology of PD. Over 20 genetic mutations have been established as underlying causes for familial parkinsonism, and more than 90 genetic risk loci are associated with the more commonly seen sporadic PD. One example is the enzyme glucocerebrosidase, which increases one's risk of developing PD 5-fold when mutated. Identification of such mutations and genetic risk loci through predictive testing can expose asymptomatic individuals who are at risk of developing PD. This testing can be particularly beneficial for those who come from ethnic backgrounds with a high prevalence of disease, including North African Berber Arabs and Ashkenazi Jews (Erkkinen et al., 2018; Tolosa et al., 2021).

### *Treatment*

Treatment for PD tends to vary based on the symptoms a patient is experiencing but often involves some combination of pharmacological and non-pharmacological components. Common medications include dopamine agonists, monoamine oxidase (MAO) inhibitors, and catechol-O-methyltransferase (COMT) inhibitors. However, the gold standard for treating PD pharmacologically is through the use of dopamine precursors such as levodopa (l-DOPA, l-3,4 dihidroxifenilalanina (Cacabelos, 2017). Still, this medication does not come without consequences. Individuals taking levodopa for prolonged periods almost universally experience a phenomenon known as the on-off cycle. The side effect is characterized by oscillations in people’s psychomotor condition, with individuals fluctuations from periods of immobility and depression to periods of higher mobility and higher energy every couple of hours (Lees, 1989). In terms of non-pharmacological interventions used to manage PD symptoms, medical practitioners frequently recommend deep brain stimulation and physiotherapy (Oertel & Schulz, 2016).

## Physical Therapy for People with Parkinson’s Disease:

As reported in a 2008 meta-analysis examining the outcomes of exercise interventions in people with PD diagnoses, exercise-based physiotherapy is demonstrated to stall or undo the functional decline in individuals’ balance, Health-Related Quality of Life (HRQOL), gait speed, physical functioning, and strength (Goodwin et al., 2008). Moreover, a longitudinal research study conducted over the course of four years in Osaka, Japan demonstrated that people with PD who engage in physical exercise had a lower rate of mortality (Kuroda et al., 1992). This evidence underscores the transformative potential of PT in managing PD, offering significant improvements in mobility, quality of life, and even longevity. This context both validates the importance of such therapeutic interventions and also opens the door to exploring more advanced, effective strategies.

Regarding the types of PT exercises healthcare professionals recommend for individuals with PD, common focuses include cardiovascular health, resistance training, balance training, and flexibility training (Salgado et al., 2013). Cardiovascular exercise yields both immediate and long-term benefits for PD symptoms. One session of structured speed-dependent treadmill training or limited progressive treadmill training has been shown to improve gait parameters such as speed and stride length (Pohl et al., 2003). Another study that used active-assisted cycling found that a single cycling session improved bradykinesia and tremors in people with PD (Ridgel et al., 2012). When cardiovascular exercise is performed consistently over the course of a few weeks to a few months, studies have shown that participants report improved mobility, reduced gait impairments, reduced fall risk and fear of falling, improved quality of life, and reduced postural instability (Cakit et al., 2007; Herman et al., 2007).

Despite the significant positive outcomes that can come from PT, there are still limitations to this treatment modality. PT can address many of the impairments associated with PD, such as the reduced strength and mobility, but the United States is currently experiencing a shortage of physical therapists (Buerhaus, 2008; “Physical therapy,” 2020). As a result, patients frequently fail to achieve the full benefits of PT due to the limited time physical therapists can dedicate to each individual patient. For example, a study of 762 people with PD identified no immediate or medium-term clinically significant benefits to participants’ quality of life or their ability to carry out activities of daily living after attending approximately four hours of physiotherapy and occupational therapy sessions over two months (Clarke et al., 2016). However, these findings speak to the use of low-dose therapeutic programs and do not render more intensive, structured PT interventions to be ineffective for this patient population.

## Robotics for Physical Therapy:

### *Stroke:*

Like people with PD, rehabilitative exercise therapy accessibility is a major social issue that stroke survivors face, and the use of robot-assisted therapies can help patients meet their individualized recovery needs and boost adherence to their treatment regimen (Kwakkel et al., 2008; Langhorne et al., 2011). Stroke is the leading cause of severe, long-term disability in the

United States, and current research efforts evaluating the use of robots in PT examines both upper- and lower-limb motor rehabilitative efforts (Tsao et al., 2023). In terms of upper-limb rehabilitation, the results have been mixed. A 2008 meta review found that, when compared to conventional physical therapy modalities, computerized assisted devices can adjust the complexity of motor tasks with a higher degree of precision via the application of constraints that optimize the intended movement. This review had a sample size of 218 patients, and the results indicate that robotic-assisted therapy of the proximal arm (shoulder-elbow level) yields more favorable outcomes than conventional methods. However, this study also found no difference between the robot and conventional therapy groups at the distal hand-wrist level (Kwakkel et al., 2008). Contrastingly, a separate wrist and metacarpophalangeal joint stroke rehabilitation study found that participants assigned to the robotic-exoskeleton PT group had greater clinical and neurophysiological improvements than the conventional PT group (Singh et al., 2021).

Lower-limb rehabilitation robotic devices also help stroke survivors achieve clinical improvements that are significantly more favorable than the outcomes associated with conventional PT alone. In a broad sense, these devices can be divided into two categories: exoskeleton robots and end-effector robots (Zhang et al., 2017). Exoskeleton robots, which can be further subdivided into treadmill-based devices and leg orthoses devices, are attached to users at multiple anatomical landmarks, and the robot’s joint axes align with the human’s joint axes. End-effector robots, which can be further subdivided into footplate-based devices and platform-based devices, are robots that connect to human users at one distal location, and the robot’s joints do not align with the user’s joints (Lee et al., 2020; Zhang et al., 2017). Most of these lower-limb rehabilitation robotic devices do successfully provide both systematic and long-term favorable outcomes, but there are several disadvantages as well. For example, the devices lack real-time control methods, so adjustments for patients' joints angles, torque, and speed are delayed. The devices also did not provide accurate data on limb force and limb position, which makes evaluating patient progress difficult. Lastly, the devices are often not portable, uncomfortable, and boring, which can lower rates of adherence to treatment protocols (Zhang et al., 2017).

### *Amyotrophic Lateral Sclerosis (ALS):*

ALS is a terminal, progressive motor neuron disorder that presents as muscle weakness, atrophy, and spasticity (Meyer, 2021). Degeneration of motor neurons located in the brainstem, motor cortex, and spinal cord translates to rapid symptom development in ALS, and rehabilitative exercise has been shown to play an integral role in maintaining physical function, as well as social interaction and quality of life (Bonafede & Mariotti, 2017; Morioka et al., 2022). While there are approved medications for ALS, only edaravone and riluzole have been shown to delay symptom development. Additionally, even for patients who are prescribed these medications, ALS is a fatal condition, and most patients will die from respiratory paralysis within three to five years of symptom onset (Pugliese et al., 2022). Thus, patient care focuses on symptom management (Morioka et al., 2022).

The nature of this condition typically involves a multidisciplinary treatment team consisting of dietitians, mental health counselors, neurologists, occupational and physical therapists, physiatrists, pulmonologists, respiratory therapists, social workers, and speech pathologists (Morioka et al., 2022). Many patients face barriers when seeking such care, and for those that can access expansive care teams and/or multidisciplinary treatment centers, there is minimal disease monitoring between appointments (Morioka et al., 2022). Technological advancements such as augmentative and assistive communication with brain-computer interfaces (BCI), eye tracking (ET) support, Internet of Things (IoT) (Bonafede & Mariotti, 2017), robotic rehabilitation, teleconsults, and wearable devices have been proposed to fill this gap (Morioka et al., 2022).

Though rehabilitative exercise has been demonstrated to be a fundamental tool in preserving physical function and there is a well-documented need for emerging technologies in ALS care, few studies have combined these concepts to evaluate the use of robotics in physical therapy (Morioka et al., 2022). However, the limited research we do have is promising. One study published in 2019 revealed that the KINARM (BKIN, Canada) robot could feasibly assess cognitive and upper-limb sensorimotor performance in ALS patients (Simmatis et al., 2019). A second study used a single-subject design to assess the benefits of supplementing conventional rehabilitative training with an upper-arm exoskeleton device called Armeo-Power (Balestrino & Schapira, 2021) (Hocoma AG, Volketswil, Switzerland) found that this treatment design improved the patient’s upper limb physical function (Portaro et al., 2019). Finally, a third study used a hybrid assistive limb (HAL; CYBERDYNE, Tsukuba, Japan) system to help improve that gait of individuals with ALS. This study is different from the previous two in that it uses bioelectrical signals from the users to support the individual in carrying out their intended motion. It, too, yielded promising outlooks, and the researchers report that repetitive, long-term training with HAL can temporarily preserve the gait function in ALS patients (Morioka et al., 2022).

Unfortunately, these research studies have significant limitations. In the project with the KINARM robot, for example, nine out of 17 subjects in this study could not complete one or more exercises. Common complaints included fatigue, trouble initiating the movement, trouble understanding the movement’s instructions, and not attempting the movement (often due to low motivation). Additionally, 12 of the 17 participants needed assistance maintaining correct posture during the assessment, two participants stated that the positioning of their upper limbs caused discomfort, and two participants stated that the robots seat caused them pain and/or discomfort (Simmatis et al., 2019). In regard to the second study, a larger sample size is vital to understanding the efficacy of the Armeo-Power device (Balestrino & Schapira, 2021; Portaro et al., 2019). Lastly, the MAL study required the presence of two physiotherapists and a physician (Morioka et al., 2022). While this is not inherently bad, it does not address the treatment accessibility problem discussed earlier.

### *Parkinson's Disease (PD):*

Integrating robots into the delivery of physical therapy presents a promising avenue for enhancing patient engagement and improving treatment outcomes. Robot-guided PT has been utilized to address mobility, strength, and flexibility impairments associated with numerous medical conditions, and home robots may be a potential solution to increase the time individuals with PD are able to engage in rehabilitation exercises. Previous work conducted in this area typically utilized wearable exoskeletons to aid patients through the rehabilitative exercises (Gryfe et al., 2022). While exoskeleton robots can be a very powerful tool for many individuals, they are very cumbersome and clunky, and they can be expensive and dangerous. Moreover, given that the target audience for rehabilitative assisting robotic devices is an older population that struggles with mobility, flexibility, and dexterity, it is critical that the technology is user-friendly and accessible. Thus, our current examination uses a small, lightweight robotic device that does not require assembly prior to each use, is capable of self-calibration, and can move around the user during an exercise session to allow the participant to independently complete a series of multiple movements.

## **Materials and Methods**

This protocol was approved by the Emory University Institutional Review Board, and the GA Institute of Technology IRB on protocol STUDY00004909 All participants signed an informed consent form prior to participation and were fully apprised of the study activities.

## Participant Recruitment

Participants with idiopathic PD in stages I-III were recruited for this study through flyers posted at Movement Disorders Clinics, presentations at Parkinson’s foundation events, clinician referrals, the Michael J. Fox Foxfinder website, the Movement Disorders unit of Emory University, PD organizations’ newsletters, support groups, educational events, and word of mouth. Interested patients were provided with additional study information by telephone.

### *Inclusion and Exclusion Criteria*

All participants were between 40-85 years old, had a clinical diagnosis of PD (Hoehn and Yahr stages I-III), and needed to be able to walk at least 10 feet, with or without an assistive device. Exclusion criteria included a diagnosis of dementia, vascular cognitive impairment, memory deficits, or other neurological disorders.

## Robotic System for Physical Therapy

This study utilized a novel physically and socially interactive robotic system called Stretch with Stretch (SWS) (Lamsey et al., 2023), which uses a Stretch RE1 robot (Kemp et al., 2022) that was modified to contain a pressurized soft bubble end effector (Kuppuswamy et al., 2020). The bubble functions as a target for participants to reach towards and repeatedly touch with different body parts while moving through an exercise session. Contact between the participant’s body and the bubble is detected by changes in the internal pressure of the bubble. Additionally, both the base and the arm of the robot are mobile, and the robot’s ambulatory workspace, defined as the volume of space within where the robot could reach, extends from the floor up to the shoulder of its user, thus enabling diverse exercises and ensuring the exercise session is tailored to the participant. A labelled diagram of the ZEST-E system is shown in Figure 2.

To cater towards each user's individual needs, the difficulty setting for each exercise was personalized in two ways for each participant, as described in (Lamsey et al., 2023). First, ZEST-E guided the user through an initial calibration that accounted for body dimensions and ROM. The calibration used 3D pose estimation to determine the dimensions of an individual's body. These dimensions were paired with simplified human kinematic models for different stretching exercises, which were parameterized with respect to the dimensions of the body parts involved in the exercise (Osokin, 2018). Second, ZEST-E also modified the difficulty level after every exercise set based on the user's performance. Repetitions per minute (RPM) was used as a performance measurement, and ZEST-E either increased the difficulty by 20%, kept the difficulty the same, or decreased the difficulty by 20% based on this assessment.

For each exercise, we approximated the motion of targeted joint with a vector and adjusted how challenging the movement was by shifting along the vector. Key components of the exercise difficulty adjustment scheme are shown in Figure 3. In this figure, the red vector $d$ corresponds to the direction in which the robot moves the target location $X_0$ to increase the difficulty of the exercise. This vector is a linear approximation of the ROM for the exercise. The participant's body part to use for the exercise is indicated by a blue circle.

The stretching exercise movements included in this study were selected to directly target motor and cognitive impairments associated with PD, and to establish a high level of user engagement. Motor impairments were addressed through exercises that challenged users to move various body parts through large-amplitude motions, and cognitive impairments were addressed through dual-tasking exercises. Dual-tasking exercises involved participants naming unique examples of concepts that fall into a given category (e.g. animals or colors) each time they completed a repetition of the assigned movement, and unique concepts were counted and recorded by SWS's speech recognition software (Zhang A, 2017).

To boost user engagement, we designed a program with significant human-robot interaction. SWS used Google's gTTS speech synthesizer to teach participants how to properly execute each exercise, and the verbal instructions were paired with a video demonstration of the exercise movement on an external screen. Additionally, ZEST-E provides verbal feedback based on the user's repetition rate and plays sound effects when a point is scored, when a task is completed, when a user hits the bubble too hard, and while scanning the user's body dimensions.

The robotics used in this study were designed to be feasible and safe for at home use. In terms of feasibility, ZEST-E was intentionally designed to be a very lightweight robotics system (~50 lbs.). It can be easily transported to a user's home in a car, and users can passively roll it around their home like a household vacuum cleaner. In regard to user safety, ZEST-E has back-drivable arms and a fail-safe run-stop button on its head that rapidly shuts off all motors. The robot is also programmed to operate slowly with low control gains. Lastly, the Stretch has internal sensors that measure the state of all its joints, and the controllers for the joints of the Stretch are designed to stop when a force threshold is reached. As such, possible collisions will tend to occur at low velocity with low forces.

## Opals Motion Capture System

We collected human motion capture data for each participant using an APDM Opals motion capture system. Opals are a wearable technological system used for motion capture

(Opals, APDM Wearable Technologies, Portland, OR, USA). The system consists of a set of 15 accelerometers rigidly mounted to the human body. The proprietary software that comes with the sensors processes the individual accelerometers' data into joint angle measurements. We recorded participants' joint angle data for each set of each exercise, as shown in Figure 4.

## Experimental Protocol

This study was performed at Wesley Woods Health Center (WWHC) of Emory University School of Medicine in Atlanta, GA. Prior to arriving at WWHC, participants completed several questionnaires related to their lifestyle and PD progression. These tools included the Demographic Information / Project Health Questionnaire, which gathered data on participant's personal, professional, and medical background; the Activities-specific Balance Confidence (ABC) scale (Powell & Myers, 1995), which assesses individuals' confidence in their ability to maintain balance in different settings; the Physical Activity Scale for the Elderly (PASE) (Washburn et al., 1993), which evaluates physical activity levels in older individuals; the Short Form 12-Quality of Life (SF12) (Grozdev et al., 2012), which assesses perceived quality of life and activity levels; and the Parkinson's Disease Questionnaire (PDQ-39) (Jenkinson et al., 1997), which quantifies how much PD symptoms impact the individual's HRQOL.

Participants were greeted by the research team and introduced to the robot upon arrival. Following this interaction, participants were asked to perform a number of motor-cognitive assessments: the Four-Square Step Test (FSST) (Dite & Temple, 2002), which evaluates how people integrate motor and cognitive stimuli; the Body Position Spatial Task (BPST) (Battisto et al., 2018), which challenges participants to maintain a neutral, upright posture while activating their navigational skills and spatial memory; a cognitive Timed Up-and-Go (TUG-C) (Podsiadlo & Richardson, 1991) mobility assessment, which is a dual-task that requires people to walk while simultaneously counting backwards by threes; a 30-second chair stand (Jones et al), where participants stand up from a chair and return to a seated position as many times as possible within 30-seconds; a 6-Minute Walk Test (6MWT) (Guyatt et al), which measures endurance; and a Functional Reach Test (de Waroquier-Leroy et al., 2014), which measures balance and flexibility. The first five assessments were only completed once, but the Functional Reach Test was performed before and immediately after the robotic exercise intervention to assess any immediate mobility improvement following the exercise session.

After completing the above assessments, participants were outfitted with a heart rate (HR) monitor used to determine physiological effort during the exercise session. Next, a set of 15 inertial sensors from the Opals motion capture marker system were placed on specific anatomical landmarks to measure ROM during each of the exercise sets (Opals, APDM Wearable Technologies, Portland, OR, USA). The research team then explained the logistics of the exercise session to participants, such as how the session would consist of six exercises: three seated, followed by three standing. We informed participants that they may take breaks whenever they need, and that we suggest an optional halfway point break between the seated and standing exercises. We also provided participants with water and snacks, and we placed chairs on either side of the participants to help with balance during standing exercises.

The seated exercises included the Seated Reach Forward (RF), the Seated Knee Extension (KE), and the Seated Calf Raise (CR), which was paired with a dual task component where participants were asked to list a different U.S. state with every repetition. The standing exercises included a Standing Reach Across (RA), which also had a dual task component where participants were asked to list a different animal with every repetition, Standing Windmills (W), and Standing High Knees (HK). The RF exercise focused on hip mobility and targeted hypometria and flexibility. The KE exercise focused on knee mobility and targeted leg strength and precision of motor control. The CR exercise focused on ankle mobility and targeted calf strength and dual tasking. The RA exercise focused on the hip, trunk, and shoulder and targeted bradykinesia, agility, and dual tasking. The W exercise focused on hip and trunk mobility and targeted flexibility, bradykinesia, and posture. The HK exercise focused on knee and hip mobility and targeted strength and endurance.

Participants went through the exercises in the order listed above, and the robot delivered verbal and video instructions before each exercise (set up shown in Figure 5). Then the robot led 10-second calibration sets for the right and left side in which the robot directly estimated each participant's ROM for the exercise. In practice, this went as follows: the robot placed the target at a location that was easy to reach. Participants were instructed to make and maintain contact with the target. The robot then moved the target away from the participant along a linear approximation of the ROM for the exercise, and the robot measured the point at which participants lost contact with the target (i.e. reached their functional ROM limit). This served as the initial calibration set point and was used as the initial difficulty setting.

Next, the participant completed two exercise sets on the right side and two exercise sets on the left side. Each exercise set lasted 30 seconds, and participants were instructed to complete as many repetitions as possible with good form. Between the first and second exercise set on each side, the robot automatically adjusted the difficulty of the exercise based on the participants' score, measured in RPM, from the previous set. RPM scores fell into one of three brackets, and this determined whether the difficulty would increase, decrease, or stay the same. As an example, scoring under 20RPM on seated forward kick would result in decreased difficulty, and scoring above 36RPM would result in increased difficulty for the next set.

Two-dimensional (RGB) videos were recorded during the session using to evaluate participants' form and execution. We also measured Rate of Perceived Exertion (RPE) and HR before, at the midway point (between seated and standing), and after the final exercise set. RPE was measured by asking how hard the participants felt like they were working on a scale of 1-10, where 1 is equivalent to sitting on the couch, and 10 is equivalent to having just finished a marathon.

Following completion of all six exercises, participants completed the standing functional reach task a second time to see if any immediate effects from exercising with ZEST-E were present in forward ROM. Participants then completed another series of questionnaires that included the Technology Attitudes Questionnaire (Rosen et al., 2013), which assess use of and attitude towards various technologies; the Usefulness, Satisfaction, and Ease of Use questionnaire (USE) (Gao et al, 2018), which measures four dimensions (ease of learning, ease of use, satisfaction, and usefulness) of usability; the Perceived Impact of Assistive Devices Scale (PIADS) (Day HI, 2003) survey, which was used to determine whether interacting with ZEST-E increased or decreased a variety of feelings about themselves such as their competence or independence, the Task Load Index (NASA TLX) (Hart & Staveland, 1988), which measures a participant's physical and mental workload during a given task; the Perceived Usefulness and Ease of Use Questionnaire (PU + PEOU) (Warkentin et al., 2007), which evaluates how participants feel ZEST-E can support them and how easy it was for them to use ZEST-E; and the Robot Opinions Questionnaire (Chen et al., 2017), which looks at how accepting participants are towards the idea of robot-guided exercise. The study concluded with a semi-structured exit interview, and participants were compensated with a $25 gift card.

## Scoring and Rating

### *Questionnaires and Assessments*

All questionnaires and motor / cognitive screening assessments were scored according to the instructions included in their initial publications.

### *Exercise Repetition Counting*

Humans manually counted the number of attempts in each exercise set (1 rep = 1 attempt). ZEST-E counted the number of times that someone hit the bubble (change in bubble pressure >= 150Pa with a 0.75s cooldown / maximum hit rate).

### *Exercise Form Scoring*

The team developed a novel assessment tool for evaluating video recordings of participants performing ZEST-E exercises. This tool consists of a survey to be completed by physical therapists, exercise specialists, or otherwise trained raters. Items from the questionnaire are given in Table 1. Each item was administered per recording of a 30-second exercise set, for 24 sets across six exercises. We aimed to capture several key pieces of information with this survey. First, we aim to quantify participants' instruction adherence rate. Then, we expand upon this rate by querying specific mistakes made during the exercise set. Finally, we identify suggested spoken phrases that a robot could say to the participant to correct their mistakes.

### *Processing Joint Angle Recordings*

We extracted key biomechanical features from the Opals joint angle recordings using MATLAB. For each exercise, we computed the maximum ROM, ROM Peak-Peak distance (P2P), exercise Repetition Rate (RR), and number of repetitions by identifying local extrema (peaks and valleys) in the joint angle recordings using signal processing. ROM is defined in (1), P2P in (2), and RR in (3), where $peak_i$ is the *i*-th peak, $valley_i$ is the *i*-th valley, and $t(peak_i)$ is the time at which *peak*$_i$ occurred. Visual examples of ROM and P2P in a knee angle recording from the seated forward kick exercise are given in Figure 6.

$$ROM = \frac{peak_i}{valley_i} \qquad (1)$$

$$P2P = t(peak_{i+1}) - t(peak_i) \qquad (2)$$

$$RR = \frac{1}{P2P} \qquad (3)$$

The signal processing pipeline was as follows. First, raw joint angle data was filtered using a 3rd order Savitzky-Golay filter. Then, candidate peaks and valleys in the joint angle data were identified using MATLAB's *findpeaks*() function. Candidate extrema were filtered by removing out of order peaks and valleys (i.e. a repetition must consist of a peak followed by a valley), and then noisy extrema were removed by dropping any remaining points that were more than 2σ from the mean. Lastly, we found the 32 second window in the recording with most repetitions. The final time window identification was important because the Opals recording included data before and after the exercise set was performed.

**Statistical Analysis**

We performed statistical analyses on both the motion capture data and the session recording ratings by physical therapists. For motion capture data, we computed descriptive statistics for the population's maximum ROM and repetition rate, such as the mean and standard deviation. Additionally, we used joint angles from research articles to anchor our ROM values to, and we ran t-tests to compare our ROM values with the outside ROM values to assess the similarity between the observed values.

For the session recording ratings, we computed summary statistics for responses to each Likert-type survey item. Free text responses to items requesting spoken feedback options that could be used to instruct participants better were scored using the python package VADER, or

*Valence Aware Dictionary for sEntiment Reasoning,* (Hutto & Gilbert, 2014) to estimate the emotional sentiment associated with each response. To assess the validity of the survey used to rate the session recordings, we computed Cohen's kappa for each Likert-type survey item to evaluate the interrater reliability between two physical therapists' ratings.

# Results

## Subjects

The subjects recruited for this study include 11 individuals (ZST102–ZST112), four males and seven females, with a PD diagnosis provided by a Movement Disorders specialist and whose symptoms range from a severity of 1-2.5 on the Hoehn and Yahr scale (Hoehn & Yahr, 1967). At the time of this study, the youngest of these participants was 61 years old, the oldest was 80 years old, and the average age of participation was 68.2 ± 5.9 years old. Eight participants identified as white/Caucasian, one participant identified as Black/African American, one participant identified as multiracial, and one participant identified as Filipino. The earliest reported year of PD diagnosis among these individuals was 2007, the most recent diagnosis was received in 2022, and the average amount of years since diagnosis was 7.1 ± 4.9 y. Participants reported an average of 1.8 ± 0.7 comorbid medical conditions, and aside from PD, the most common conditions participants experienced were high blood pressure (reported by five participants) and heart problems (reported by two participants). Study participants had an average of 17.5 ± 2.1 y of education, with one participant reporting that they have an associate's degree, and the remaining 10 participants having a bachelor's degree or higher. Nine individuals reported that English is their first language, one individual's first language was Tagalog, and one individual's first language was Hebrew. All participants were fully proficient in English, and no participants experienced a language barrier when following spoken ZEST-E's spoken instructions (Table 2).

One participant noted that they use a crutch at night after their medications have worn off, and no other participants reported that they use a mobility aid. This participant did not need to use their assistive device while exercising with the robot. Lastly, 10 of the individuals were currently on one or more prescribed antiparkinsonian medications that they were encouraged to take on the day of their assessment with ZEST-E. Of these 10 participants taking antiparkinsonian medications, eight are prescribed Carbidopa or Levodopa (Table 2).

## Range of Motion

### *Characterization*

For each ZEST-E exercise, we computed the maximum ROM. ROM for each exercise is given in Figure 7 as well as Table 3. The four joints we focused on were the hips, the knees, the ankles, and the torso. More specifically, we measured knee extension, knee flexion, hip flexion, ankle plantarflexion, and torso twist. Flexion (fig. 8) is defined as a movement that decreases the angle between the bones connected by the joint of interest, whereas extension refers to a movement that increases the angle between the bones connected by the joint of interest (Gordon Betts et al., 2013). Thus, a large knee flexion ROM is associated with a small change in knee angle, and a large knee extension is associated with a large change in knee angle. Seated knee extension (KE) and standing high knees (HK) are the two exercises that targeted the knee joint, and while the KE was an extension exercise and HK was a flexion movement, both lead participants through a similar ROM. KE measured to 59.2 ± 12.2 degrees and HK measured to 52.1 ± 15.7 degrees. In terms of hip flexion, standing windmills (W) and HK had the largest

ROM values of 65.6 ± 17.9 degrees and 68.4 ± 15.9 degrees, respectively. The seated reach forward (RF) and standing reach across (RA) exercises had smaller hip flexion ROMs of 23.8 ± 10.5 degrees  and 13.0 ± 9.2 degrees, respectively. Seated calf raise (CR) is the only exercise that measure ankle plantarflexion, and the maximum ROM for this exercise averaged out to 41.5 ± 13.0 degrees. RA and W are the two exercises that measured torso twist, and these ROM values were 17.5 ± 6.9 degrees and 26.2 ± 10.3 degrees, respectively.

### *Range of Motion vs. Difficulty*

In addition to the overall ROM data, we also characterized the ROM data vs ZEST-E difficulty setting. Participants saturated ZEST-E's difficulty model, and most sets were at or near maximum difficulty. There was no useful or substantial regression correlation between difficulty and ROM for all exercises except for the seated calf raises (fig. 7). For this exercise, the robot often moved beyond the participant's max ROM. Thus, the participants' ankle plantarflexion ROM values remained relatively constant across various difficulty levels.

## Repetition Rate

### *Characterization*

Repetition rate data was extracted from the Opals time signal data as described in the *Processing Joint Angle Records* subsection above. The three seated exercises – RF, KE, and CR – measured RR with respect to one joint movement each. The RF hip flexion RR was defined as 0.7 ± 0.1 Hz, the KE knee extension RR was defined as 0.8 ± 0.1 Hz, and the CR ankle plantarflexion RR was defined as 0.7 ± 0.3 Hz. In contrast, the three standing exercises – RA, W, and HK – measured RR with respect to two joint movements. Except for RA, RR was consistent between different joint movements measured from the same standing exercise. The W hip flexion RR was measured to be 0.6 ± 0.1 Hz, and the W torso twist RR was measured to be 0.6 ±

0.1 Hz. Following a similar pattern, the HK hip flexion RR was measured to be 0.7 ± 0.2 Hz, and the knee extension RR was measured to be 0.7 ± 0.2. On the other hand. The RA hip flexion RR was 0.3 ± 0.2 Hz, and the RA torso twist RR was 0.5 ± 0.1 Hz (Figure 10, Table 4).

### Repetition Rate vs. Difficulty

As shown in Figure 11, there was no correlation between the RR of an exercises and ZEST-E's difficulty setting. However, since Figure 11 used Opals ROM data to calculate RR, what can be concluded from the data is that participants moved through a significant ROM on the CR exercise even when they did not make contact with ZEST-E's target.

## Physical Therapist Rating

### ZEST-E Instruction Adherence

Two physical therapists, Rater A and Rater B, recorded whether participants adhered to ZEST-E's verbal (spoken from the robot) and visual instructions (video) (Figures 12 and 13, respectively), and we calculated Cohen's Kappa (K) values to measure the interrater reliability for these measurements (Table 5) (McHugh, 2012). According to both raters, participants struggled to perform the exercises as demonstrated by the video significantly more than they struggled to abide by the verbal instructions ZEST-E provided.

The raters were generally consistent when identifying errors in following ZEST-E's instruction. Regarding the verbal instruction error rates, there was almost perfect agreement for RF (Rater A = 0.0% error rate; Rater B = 5.6% error rate; K = 0.87), none to slight agreement for FK (Rater A = 7.5% error rate; Rater B = 40.0% error rate; K = 0.18), substantial agreement for CR (Rater A = 27.5% error rate; Rater B = 22.5% error rate; K = 0.66), almost perfect agreement for RA (Rater A = 38.9%% error rate; Rater B = 50.0% error rate; K = 0.89), substantial agreement for W (Rater A = 7.9% error rate; Rater B = 0.0% error rate; K = 0.78), and almost perfect agreement for (Rater A = 0.0% error rate; Rater B = 0.0% error rate; K = 1.00). In terms of the video instruction error rates, there was almost perfect agreement for RF (Rater A = 47.2% error rate; Rater B = 52.8% error rate; K = 0.89), substantial agreement for FK (Rater A = 77.5% error rate; Rater B = 82.5% error rate; K = 0.77), moderate agreement for CR (Rater A = 52.5% error rate; Rater B = 30.0% error rate; K = 0.56), almost perfect agreement for RA (Rater A = 41.7% error rate; Rater B = 50.0% error rate; K = 0.92), substantial agreement for W (Rater A = 97.4% error rate; Rater B = 89.5% error rate; K = 0.80), and substantial agreement for HK (Rater A = 81.8% error rate; Rater B = 81.8% error rate; K = 0.60).

### *ZEST-E Exercise Deviations*

Figure 14 highlights the different types of mistakes participants made while completing each of the six exercises in the sequence. The mistake types varied by exercises, and the survey used by physical therapists to record this data included an “other” selection that allowed them to report a mistake not listed.

For the RF exercise, Rater A and Rater B both agreed that there was no detectable error in slightly less than half of the exercise sets (Rater A 47.5%; Rater B 45.0%), and the participants did not return to an upright seated position between repetitions in slightly more than half of the exercise sets (Rater A 52.5%; Rater B 55.0%). Rater A reported a 5.0% prevalence of “other” errors, and Rater B reported a 17.5% prevalence of “other” errors. For the FK exercise, Rater A and Rater B disagreed on what the most common error was, with Rater A believing that it was not returning the kicking leg back to a resting position between repetitions, and Rater B believing that the most common error type was the participants not having their hips against the back of the chair. Also notable is the fact that Rater A recorded a 9.1% frequency of “other” errors while Rater B recorded a 54.6% frequency of “other” errors. For the final seated exercise, CR, both raters did not identify any exercise deviations in approximately 60% of the exercise sets (Rater A 59.1%; Rater B 65.9%). The raters disagreed on what the most common deviation was, with Rater A believing that it was the participants lifting their toes off the floor and Rater B believing that it was a mistake not listed on the survey. However, both raters agreed that the participant lifted their toes off the floor in approximately 20% of the exercise sets (Rater A 22.7%; Rater B 20.5%).

In regard to the mistakes made during the RA exercise, Rater A reported no deviations in 50.0% of the exercise sets, and they also reported that the participant did not return to a neutral post between repetitions for 50.0% of the exercise sets. Rater B reported similar frequencies, but the frequency for no error was slight less than 50.0% (45.0%) and the frequency for not returning to a neutral post between repetitions was slightly more than 50.0% (55.0%). Both raters reported witnessing an unlisted error in less than 10% of these exercise sets (Rater A 2.5%; Rater B 7.5%). For the W exercise, Rater A noted that no participants executed the movement correctly and the participants bent their legs in 100% of the exercise sets. This rater also noted that the participant did not return to a neutral position between exercise repetitions in 45.2% of the exercise sets, and that there were no other mistakes made that were not listed on the survey. Rater B noted that 9.5% of the exercise sets were done with correct form, 90.5% of the exercise sets were conducted with bent knees, the participant did not return to a neutral position between repetitions in 52.4% of the exercise sets, and the participant made an error not listed on the survey in 16.7% of exercise sets. For the final standing exercise, HK, the raters recorded the same frequency value (18.2%) for the number of sets executed with correct form. The raters also recorded similar frequency values for the number of exercise sets where the participant lost balance (Rater A 9.1%; Rater B 11.4%). and for the number of exercise sets where the participant made a mistake not listed on the survey (Rater A 72.7%; Rater B 81.8%). However, only Rater A recorded that there were any sets in which the participant did not step back to the ground between repetitions or that there were any sets in which the participant missed the target. The frequency values for these errors are 22.7% and 13.6%, respectively.

### *ZEST-E Exercise Deviation Causes*

In addition to calculating the frequency of different error types of each exercise, we also asked the physical therapist raters about what they thought contributed to the participants' mistakes (fig. 15). For the RF, both raters reported that misunderstanding instructions was an underlying cause of the errors in slightly over half of the exercise sets (Rater A 52.5%; Rater B 55.0%). Rater A attributed the remainder of errors to speed/neglecting form in 7.5% of exercise sets and to something not listed on the survey ("other") in 20.0% of exercise sets. Rater B attributed the remainder of errors to speed/neglecting form in 15.0% of exercise sets and to something not listed on the survey ("other") in 2.5% of the exercise sets. For the FK, both raters again hypothesized that the most common cause of error for this exercise was misunderstanding instructions. Only Rater A thought that the errors were caused by a participant being unable to perform the motion, and they reported this as a deviation cause in 25.0% of exercise sets. Also notable is that Rater A attributed the cause of exercise deviations to speed/neglecting form twice as frequently as Rater B (Rater A 52.3%; Rater B 27.3%). For the last seated exercise, CR, both raters hypothesized that the most common cause of error was something not listed in the survey. Again, only Rater A thought that errors were caused by an inability to perform the motion properly, and they reported this as a deviation cause in 31.8% of exercise sets. Rater A was also the only rater to report that speed/neglecting form could be underlying the mistakes, and they reported this in 4.6% of the exercise sets. Additionally, Rater B reported that misunderstanding instructions led to errors at over twice the rate of Rater A (Rater A 11.4%; Rater B 25.0%).

In terms of the RA, Rater B hypothesized that misunderstanding instructions was the most common reason a participant to perform the exercise incorrectly, while Rater A hypothesized that this was the least common cause of a form error (Rater A 10.0%; Rater B 47.5%). Rater A also attributed the cause of errors to fatigue almost twice as frequently as Rater B (Rater A 32.5%; Rater B 17.5%). For the W exercise, the raters agreed that misunderstanding was the most common cause of a form error, and Rater A and Rater B both reported this as the deviation cause in 90.5% of the exercise sets. The raters also agreed that the second most common cause of a form error was speed/neglecting form (Rater A 45.2%; Rater B 57.1%), but only Rater A thought there might be something not on the chart that led to participants not executing the exercise properly. Additionally, Rater A listed that fatigue may have led to form errors in 28.6% of the exercise sets, while Rater B listed this for 2.4% of the exercise sets. Finally, for the last standing exercise, HK, the raters again had very different hypotheses for what led the participant to perform the exercise incorrectly. Rater A attributed the cause of error to fatigue in 72.7% of exercise sets, misunderstanding instructions in 27.3% of exercise sets, speed/neglecting form in 68.2% of exercise sets, and something not listed on the survey in 9.1% of exercise sets. Meanwhile, Rater B attributed the cause of error to fatigue in 6.8% of exercise sets, misunderstanding instructions in 54.6% of exercise sets, speed/neglecting form in 36.4% of exercise sets, and something not listed on the survey in 22.7% of exercise sets.

### *DPT Rating: VADER Sentiment Scores*

VADER is a sentiment analysis algorithm we used to evaluate the raters' attitude towards the participants' performance. The scores relate to specific feedback raters would give to correct behavior, with score of +4 representing a highly positive sentiment, a score of zero representing a neutral sentiment, and a score of -4 representing a highly negative sentiment. Our results indicate that the raters had a positive or neutral attitude towards the participants' performance, as shown in Figure 16.

## Discussion

To our understanding, this is the first study that gathered ROM data, RR data, and input from physical therapists to evaluate the feasibility of home robotics to guide people with PD through a PT regimen. Our results from are consistent with the literature highlighting the potential for robot-guided PT to supplement conventional PT.

### ROM measurement and application in Exercise:

#### ZEST-E ROM During Twisting Motions Compared to External Source

Torso twist was measured in our study by both RA and W, and torso twist comparison values were taken from a paper titled "Trunk Range of Motion Is Related to Axial Rigidity, Functional Mobility and Quality of Life in Parkinson's Disease: An Exploratory Study" (Cano-de-la-Cuerda, 2020). The external source separated left and right torso twist ROM values (30.2 ± 18.7 degrees and 32.2 ± 10.7 degrees, respectively), and we combined this data for our t-test calculations (31.2 ± 14.6 degrees). When executing W, the degree of rotation participants achieved was consistent with the degree of rotation people with PD achieved in the literature ($p = 0.2936$). The average maximum torso twist recorded during the RA was significantly lower than the value found in the literature, but this does not render RA to be an ineffective PT exercise for this population because it targets muscle weakness and balance concerns characteristic of PD.

### *ZEST-E Hip ROM Compared to External Source*

The anchor hip ROM values from the literature are significantly greater than the values participants reached while exercising with ZEST-E. In a study of 231 women, and 205 men, at around 60 years old, women had average hip flexion value of 114 degrees and men had an average hip flexion value of 102 degrees; these values decreased by 7 degrees per decade in women and by 6 degrees per decade in men. However, these values do not come from a sample of older adults with PD, and the average ROM from the literature was obtained by instructing individuals to lean backward as far as possible and then to fold forward as far as possible (Stathokostas et al., 2013). In contrast, none of ZEST-E's exercises involve participants bending backward. While both sets of data come from a flexion motion, a movement that brings the knees in towards the chest, decreasing the angle between one's stomach and one's legs, our data begins with participants in an upright position, and the external data begins with participants in an extended, arched position. Moreover, when the HK hip ROM values were compared with average hip flexion and extension values of 26 healthy younger adults (20 ± 1 years old), the ROM values from exercising with ZEST-E are similar to or significantly greater than those during activities of daily living (ADL) such as putting on pants with your non-dominant leg while standing, side-stepping into the bath leading with your non-dominant leg, and getting out of the bath leading with your nondominant leg (Hyodoa et al., 2017).

### *ZEST-E Knee ROM Compared to External Source*

We also compared knee flexion ROM values from ZEST-E to the average values from a group of 20 older adults with PD after 12 weeks of exercise therapy intervention, and we found that they are significantly different (Wan et al., 2021). During HK, participants achieved an average knee flexion ROM of 52.1 ± 15.7 degrees, while after three months of Health Qigong

Exercises, individuals had average knee flexions of 84.0 ± 18.8 degrees on the left and 84.6 ± 16.4 degrees on the right. However, it is important to note that our values came from a single exercise session, not 12 weeks of therapeutic intervention. While Wan and colleagues did not report ROM values after the first day of treatment, they did report ROM at the six-week mark, and these values do align with the values from our study (p=0.2811 left; p= 0.6879 right). Furthermore, these knee ROM values were obtained by having participants lay on their back and lift their knee to their chest. For the HK exercise, participants had to do lift their knee while balancing on one foot, which takes considerably more balance.

### *ZEST-E Ankle ROM Compared to External Source*

The ZEST-E study measured ankle plantarflexion during the CR exercise, and the recorded average maximum ROM during this movement was 41.5 ± 13.0 degrees. When compared to the ankle plantarflexion of 26 healthy younger adults during ADL, the ROM achieved through exercising with ZEST-E exceeds that of all 22 recorded ADL. The two entries in this external study with the largest ankle plantarflexion were putting on pants with one's dominant leg while sitting and putting on pants with one's dominant leg while standing. The former had an ankle plantarflexion ROM value of 37 ± 8 degrees, and the latter had an ankle plantarflexion ROM value of 37 ± 7 degrees (Hyodoa et al., 2017).

## Physical Therapy Ratings of Exercise Performance/Quality

### *Quality of Exercise*

We presented a survey to two physical therapists to gather data on both verbal and video instruction adherence, form error types, and hypothesized form error causes. For all six exercises, both raters reported that patients were less adherent to video instructions than to verbal instructions. Interestingly, there was an inverse-like relationship between verbal instructions error rate and video instructions error rate for each exercise. According to Rater A, the two exercises that had the highest verbal error rates (CR and RA) had the lowest video error rates. Similarly, according to Rater B, the two exercises that had the lowest verbal error rates (W and HK) have the highest video error rates. However, this is not a perfectly inverse relationship. As reported by Rater B, FK has the second highest verbal instruction error rate and is tied with HK for the second highest video instruction error rate. Nevertheless, it is possible that the inverse relationship demonstrated in the adherence rates of some exercises may be because participants elected to either focus on the verbal or the video instructions. Future studies should explore if instruction adherence rates improve when participants are only told to focus on one information source for exercise explanations.

### *Common exercise mistakes and hypothesized error causes*

The survey answer selections for form error causes were consistent for all six exercises, and both raters suspected that most mistakes were due to interpretation challenges. Rater A hypothesized that “misunderstanding instructions” was the leading cause of error for three out of six of the exercises, and Rater B hypothesized that this was the leading cause of error for five out of six of the exercises. As explained above, one way to mediate this concern may be directing participants to focus on one information source for exercise explanations instead of two. Additionally, though, it is probable that users will not experience such high rates of misunderstanding instructions when ZEST-E is commercially available. In our pilot study, we gathered data from participants during their first time exercising with the robot, which was also their first time performing these exercises. We did not explain the exercises ourselves, the only verbal instructions provided came from the robot, and we did not correct the participants when they were working out with improper form. In practice, we envision that ZEST-E will be used as an at-home exercise partner while people with PD are under the care of a PT team. ZEST-E users will not be learning new exercises from a robot. Rather, the robot will be guiding users through exercises that are similar to or the same as those they are assigned to do during their PT appointments. With the HK for example, the use of ZEST-E's sensor to count repetitions may be new, but if the user has been working on HK with their physical therapist, the general motion is already familiar to them. Thus, the reported frequency at which participants are hypothesized to have made errors because of misunderstood instructions, as well as the overall error rates for each exercise, are likely overestimates of what we would see in practice.

The survey options for form error types included unique selections for each exercise as well as an "other" option that allowed PT raters to submit their own response. Nevertheless, there are still commonalities in the mistakes detected across exercises, such as improper form between repetitions (recorded as "did not sit back up" for RF, "did not swing leg back down" and "hips not against back of chair" for FK, "lifted toes off floor" and "did not lower heel to floor" for CR, "did not return to neutral pose" for RA, "did not stand back up" for W, and "did not step back to ground" for HK). While it is likely that we would not see these errors as frequently in practice, as explained above, this concern can also be addressed by instructing users to direct focus externally to additional targets. For example, sensors can be placed on the back of the user's chair during RF that make a sound when the participant returns to an upright position between repetitions, and a band stretched around the front legs of the user's chair can provide the participant with a target when swinging their leg down between FK repetitions.

## Limitations

ZEST-E often did truly move beyond the participant's maximum ROM during CR. We hypothesize that this is, in part, because the human ROM for this exercise is small and well within the robot’s workspace. We suspect that limitations in the formulation of the difficulty model played a role in this observation, as the existing formulation did not allow for hard enough exercises to truly max out people’s capabilities (Lamsey et al., 2023). Additionally, this study used a small sample size (n=11) and included no control group.

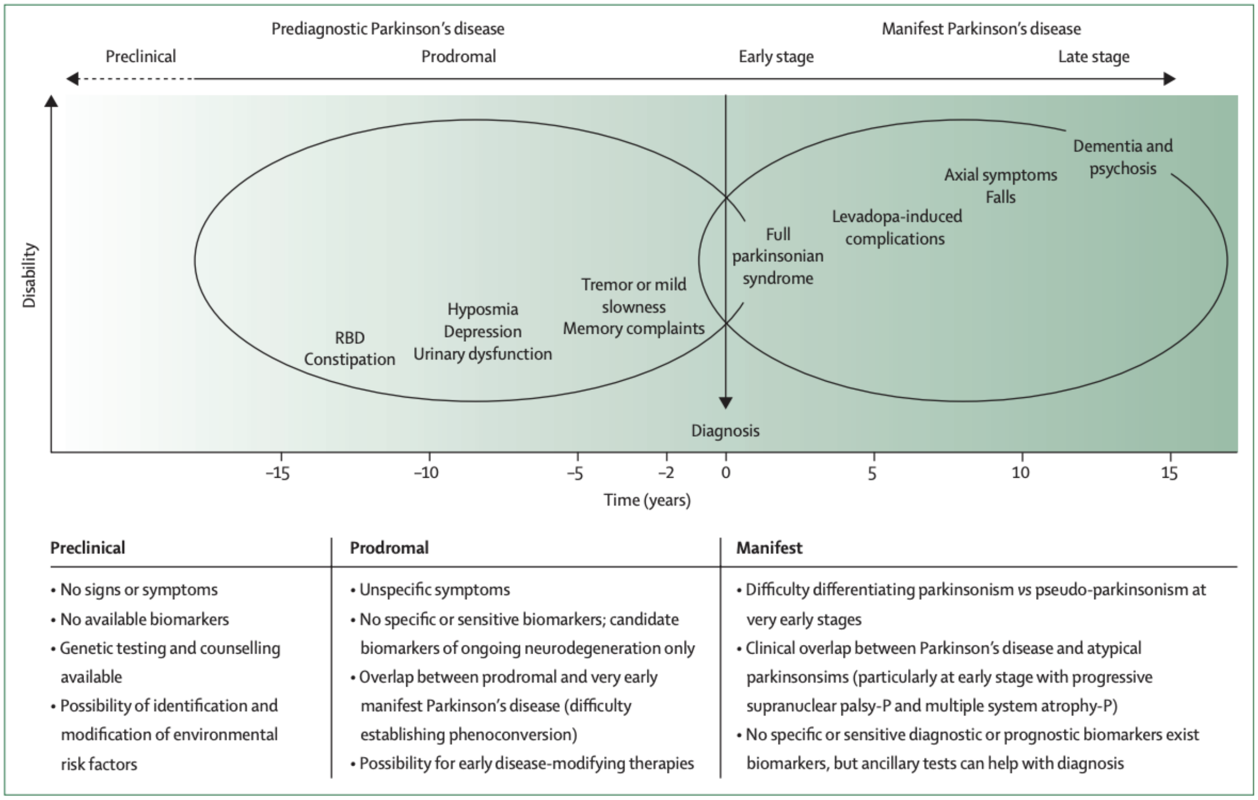
### Next Steps

Moving forward, we should ensure the exercise difficulty model is scaled to each participant and expand the range of difficulties ZEST-E can accommodate (fig. 3). Upcoming studies should include a PD control group that is exercising at home without ZEST-E to get a better understanding of how robot-assisted PT can slow symptom progression. Future work should consider incorporating additional targets for participants to focus on while exercising. Lastly, follow-up studies should be designed in a manner that approximates the anticipated user’s experience using a home-robotics system to supplement ongoing PT treatment. For example, this may include an initial exposure to the home exercises at PT appointments and requiring the participant to initiate their exercise session independently to evaluate ease of use.

## Conclusions

The present study shows that a robot-guided physical therapy device can successfully lead people with PD through a ROM that is largely consistent with the normative values in the literature. Our findings indicate that instruction adherence was a challenge for users, which we hypothesize may be due to the use of two modalities for instruction delivery and the unfamiliarity participants had with the exercises.

# Figures and Graphs



| Preclinical | Prodromal | Manifest |
|---|---|---|
| • No signs or symptoms<br>• No available biomarkers<br>• Genetic testing and counselling available<br>• Possibility of identification and modification of environmental risk factors | • Unspecific symptoms<br>• No specific or sensitive biomarkers; candidate biomarkers of ongoing neurodegeneration only<br>• Overlap between prodromal and very early manifest Parkinson's disease (difficulty establishing phenoconversion)<br>• Possibility for early disease-modifying therapies | • Difficulty differentiating parkinsonism *vs* pseudo-parkinsonism at very early stages<br>• Clinical overlap between Parkinson's disease and atypical parkinsonsims (particularly at early stage with progressive supranuclear palsy-P and multiple system atrophy-P)<br>• No specific or sensitive diagnostic or prognostic biomarkers exist biomarkers, but ancillary tests can help with diagnosis |

**Figure 1:** PD symptoms and disease stage (Tolosa et al., 2021).

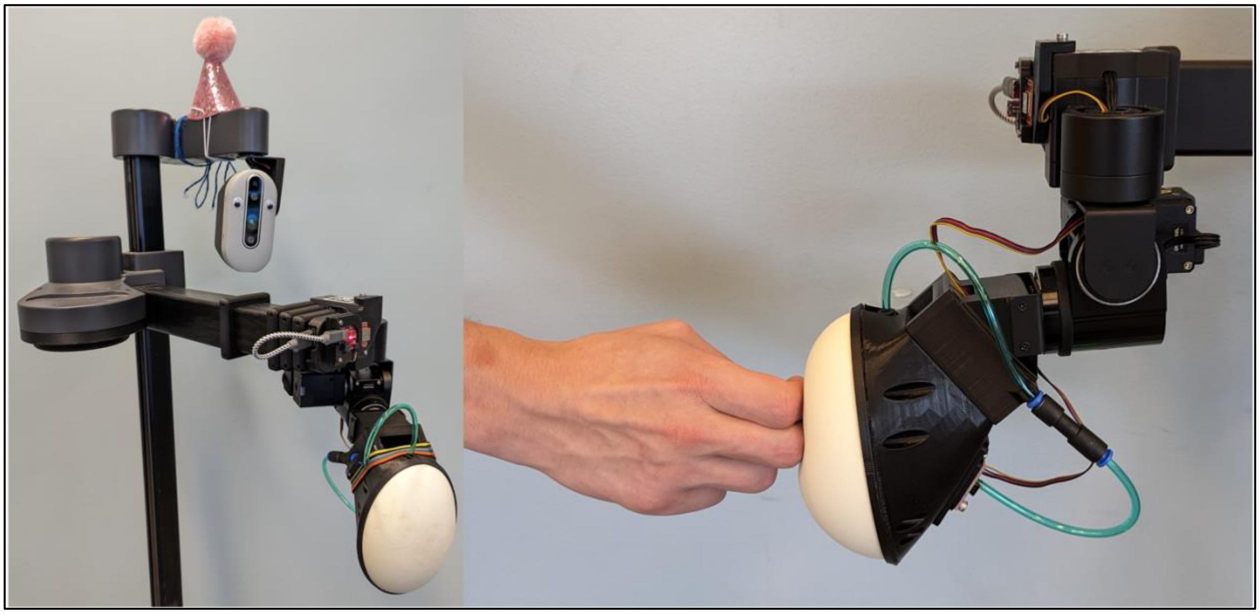


**Figure 2:** ZEST-E System (left) and pressurized soft bubble end effector (right).

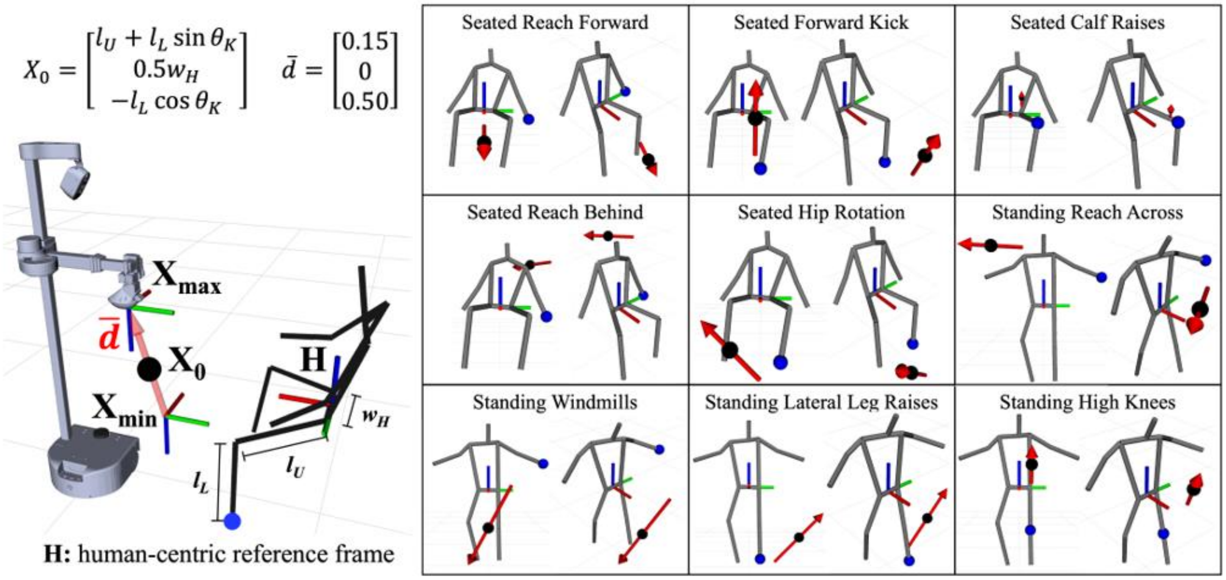


**Figure 3:** (Left) Exercise model for a seated forward kick. The location of the 50% difficulty point X0 is a function of relevant body dimensions (meters) and is shown as a black sphere. The difficulty vector ¯d is specified absolutely (meters) and is shown as a red arrow. The body part used to make contact with the robot during the exercise is indicated by a blue sphere. Front and isometric views of each of nine exercise models (Lamsey et al., 2023).

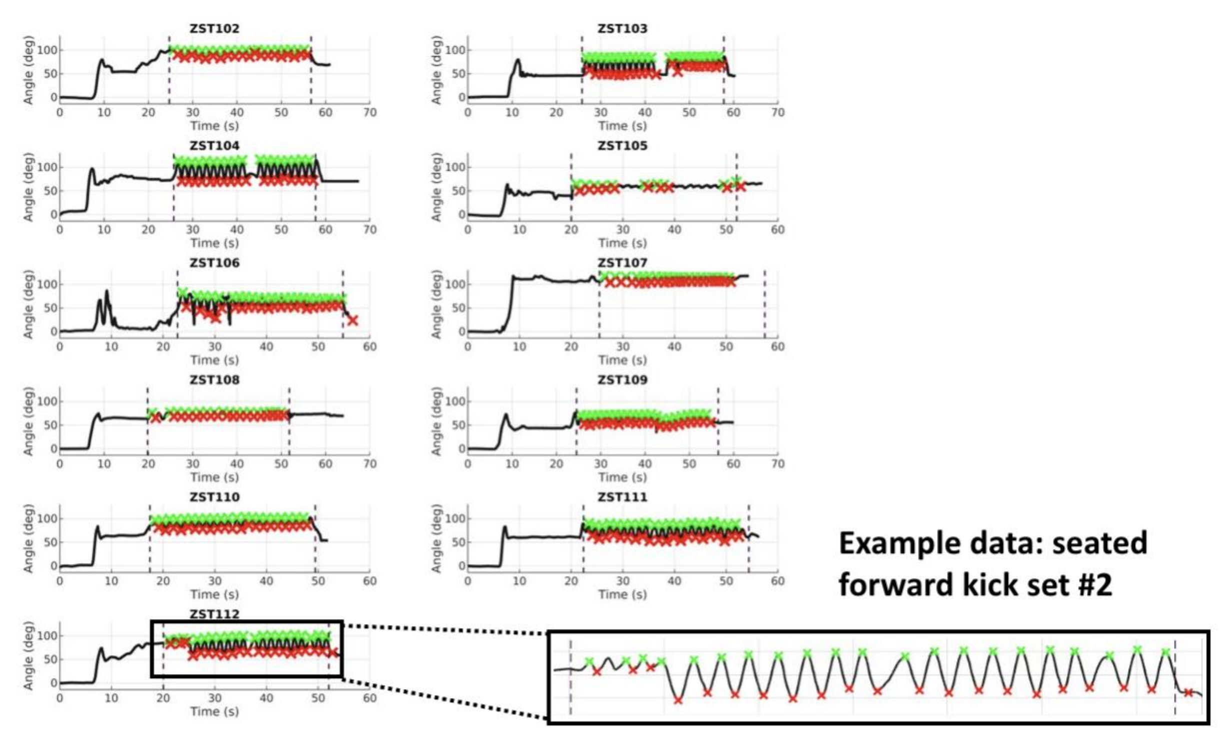


**Figure 4:** An example time series of joint angles during the seated forward kick exercise.

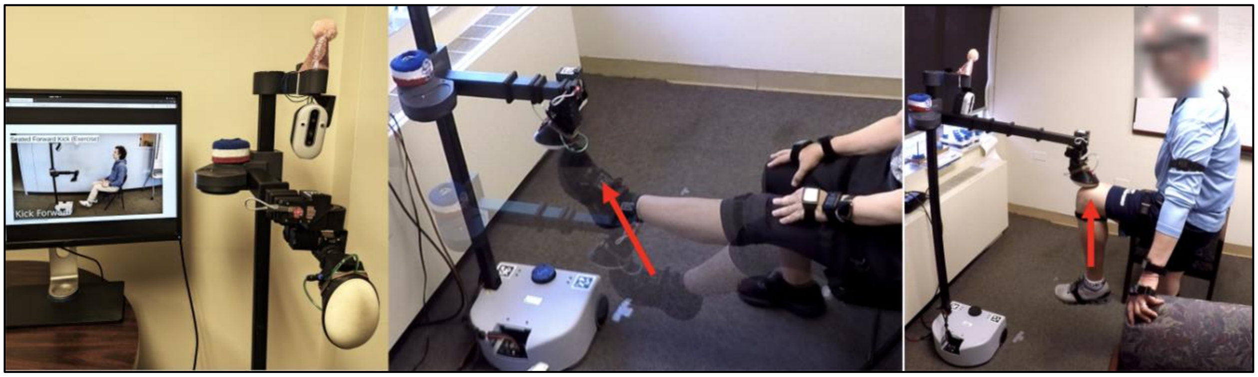


**Figure 5:** (Left) Stretch with Stretch (SWS), a system for personalized robot-led physical therapy. Video instructions are shown on an adjacent screen. (Middle) SWS sampling the range of motion of a participant with PD. A participant with PD performing a standing high knees exercise (Lamsey et al., 2023).

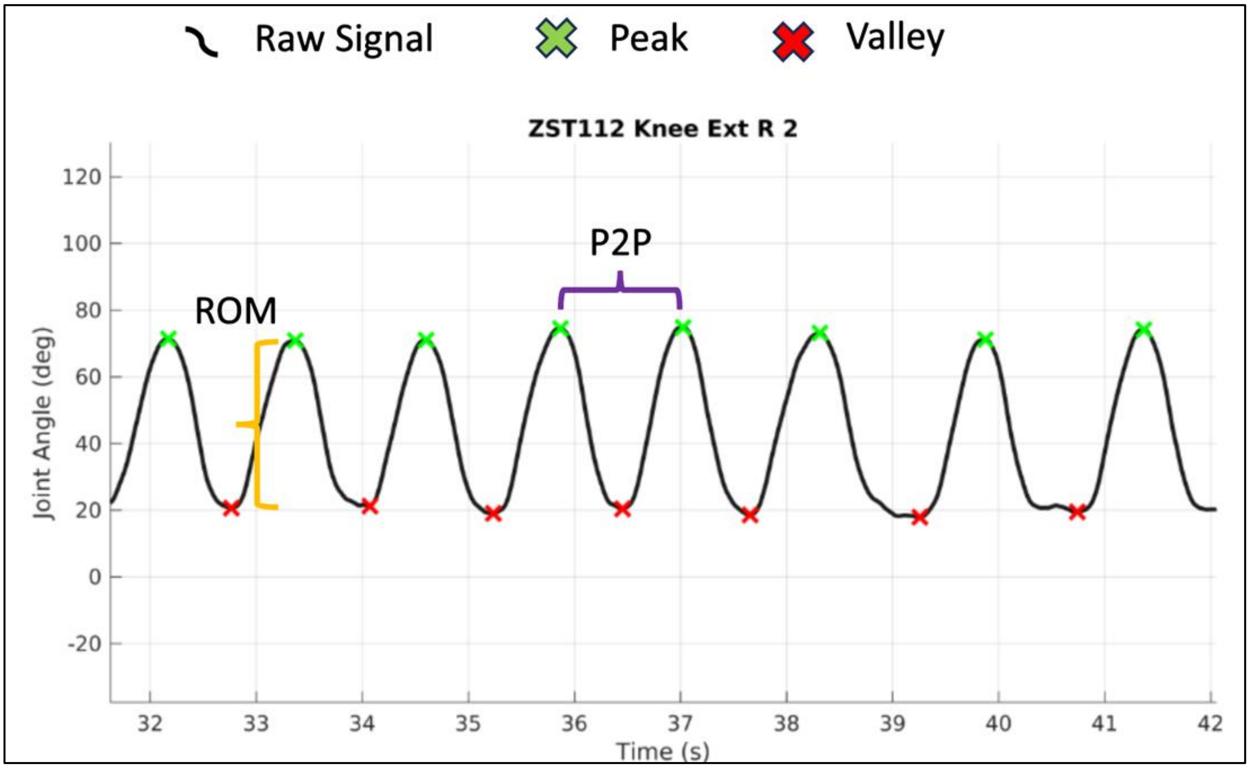


**Figure 6:** Example signal processing of biomechanical data using MATLAB. ROM and Peak-Peak distance (P2P) are shown.

| *i* | Survey Item | Intent |
|---|---|---|
| 1 | Did the participant perform set # of [the exercise] with their right or left [body part]? | Ensure synchronization with video recording |
| 2 | Did the participant perform the physical component of [exercise] set # according to the robot's spoken instructions for more than half (50%) of repetitions?<br>The robot said: [robot's spoken instructions] | Assess whether the participant followed the robot's spoken instructions |
| 3 | Did the participant perform [exercise] set # in the same manner as the video example for more than half (50%) of repetitions?<br>Full description: [description] | Assess whether the participant mimicked the video demonstration showed on an adjacent screen |
| 4 | Did the participant perform the cognitive component of [exercise] set # according to the robot's spoken instructions for more than half (50%) of the repetitions?<br>The robot said: [robot's spoken instructions] | Assess how well a participant completed the dual-tasking component of ZEST-E |
| 5 | For [exercise] set #, please indicate how the subject deviated from the intended video or verbal instructions. Mark deviations which occurred for more than half (50%) of repetitions. Please select all that apply. | Obtain expert identification of mistakes made by participants in the video recording |
| 6 | For [exercise] set #, what appeared to contribute to deviations from the intended video or verbal instructions? Mark deviations which occurred for more than half (50%) of repetitions. Please select all that apply. | Obtain expert hypotheses about why the participants deviated from the instructions |
| 7 | How would you verbally instruct the person to adjust their performance of Seated Calf Raises? (n/a if none) | Obtain suggested feedback phrases for the robot to use in the future |

**Table 1:** Survey items contained in the exercise recording rating questionnaire.

| Record ID | Sex | Age | Ethnic background | PD Duration (y) | ABC average score | SF12 PCS | SF12MCS | PDQ-39SI | PASE Total Score |
|---|---|---|---|---|---|---|---|---|---|
| **ZST102** | F | 80 | Other (Filipino) | 6 | 81.875 | 54.1 | 52.8 | 14.6 | 104.6 |
| **ZST103** | F | 69 | White/Caucasian | 3 | 97.5 | 46.4 | 54.4 | 9.6 | 427.9 |
| **ZST104** | F | 68 | White/ Caucasian | 16 | 82.5 | 49.13 | 48.7 | 22.9 | 121.6 |
| **ZST105** | M | 62 | White/Caucasian | 11 | 70.625 | 34.9 | 44.5 | 51.5 | 175.0 |
| **ZST106** | F | 69 | Black/African American | 9 | 85.625 | 50.9 | 47.6 | 7.6 | 85.8 |
| **ZST107** | M | 71 | White/Caucasian | 1 | 93.75 | 50.4 | 43.0 | 18.0 | 173.4 |
| **ZST108** | M | 62 | White/Caucasian | 4 | 69.375 | 42.7 | 45.0 | 23.5 | 207.4 |
| **ZST109** | M | 62 | White/Caucasian | 15 | 78.125 | 39.19 | 38.6 | 21.6 | 61.6 |
| **ZST110** | F | 70 | White/Caucasian | 4 | 96.25 | 62.6 | 43.4 | 3.9 | 168.1 |
| **ZST111** | F | 61 | White/Caucasian | 2 | 100 | 63.4 | 47.6 | 5.2 | 329.2 |
| **ZST112** | F | 76 | Multiracial | 7 | 85 | 47.7 | 46.2 | 12.4 | 226.2 |

**Table 2.** Participant demographics for the ZEST-E user study (record identification, sex, ethnic background, and PD duration) (left five columns) and participant questionnaire responses (Activities-Specific Balance Confidence (ABC) average score, Short Form 12 Physical Component Score (SF12 PCS), Short Form 12 Mental Component Score (SF12 MCS), Parkinson’s Disease Questionnaire Summary Index (PDQ-39SI), and Physical Activity Scale for the Elderly (PASE) total score) (right five columns).

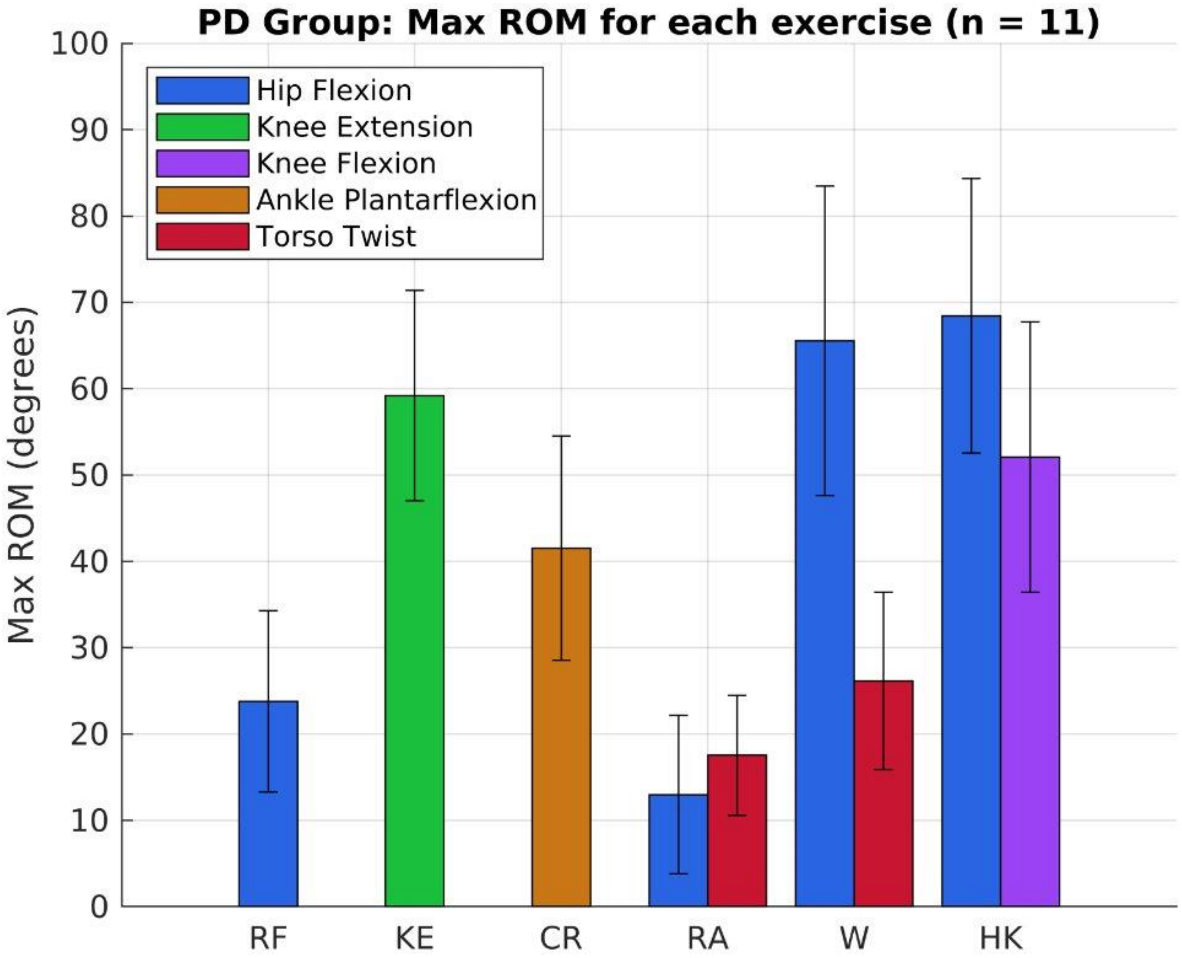


**Figure 7:** Average maximum ROM achieved by PWP (*n*=11) for each ZEST-E exercise. RF: Seated Reach Forward; KE: Seated Knee Extension; CR: Seated Calf Raise; RA: Standing Reach Across; W: Standing Windmills; HK: Standing High Knees. Each seated exercise measured ROM at one joint angle; each standing exercise measured ROM at two joint angles.

| Exercise | Joint | ROM (degrees) |
|---|---|---|
| Seated Forward Reach | Hip Flexion | 23.775 ± 10.494 |
| Seated Knee Extension | Knee Extension | 59.205 ± 12.191 |
| Seated Calf Raises | Ankle Plantarflexion | 41.52 ± 13.005 |
| Standing Reach Across | Hip Flexion | 12.982 ± 9.168 |
| Standing Reach Across | Torso Twist | 17.535 ± 6.943 |
| Standing Windmills | Hip Flexion | 65.552 ± 17.904 |
| Standing Windmills | Torso Twist | 26.157 ± 10.253 |
| Standing High Knees | Hip Flexion | 68.442 ± 15.899 |
| Standing High Knees | Knee Flexion | 52.086 ± 15.656 |

**Table 3:** Average maximum ROM data.

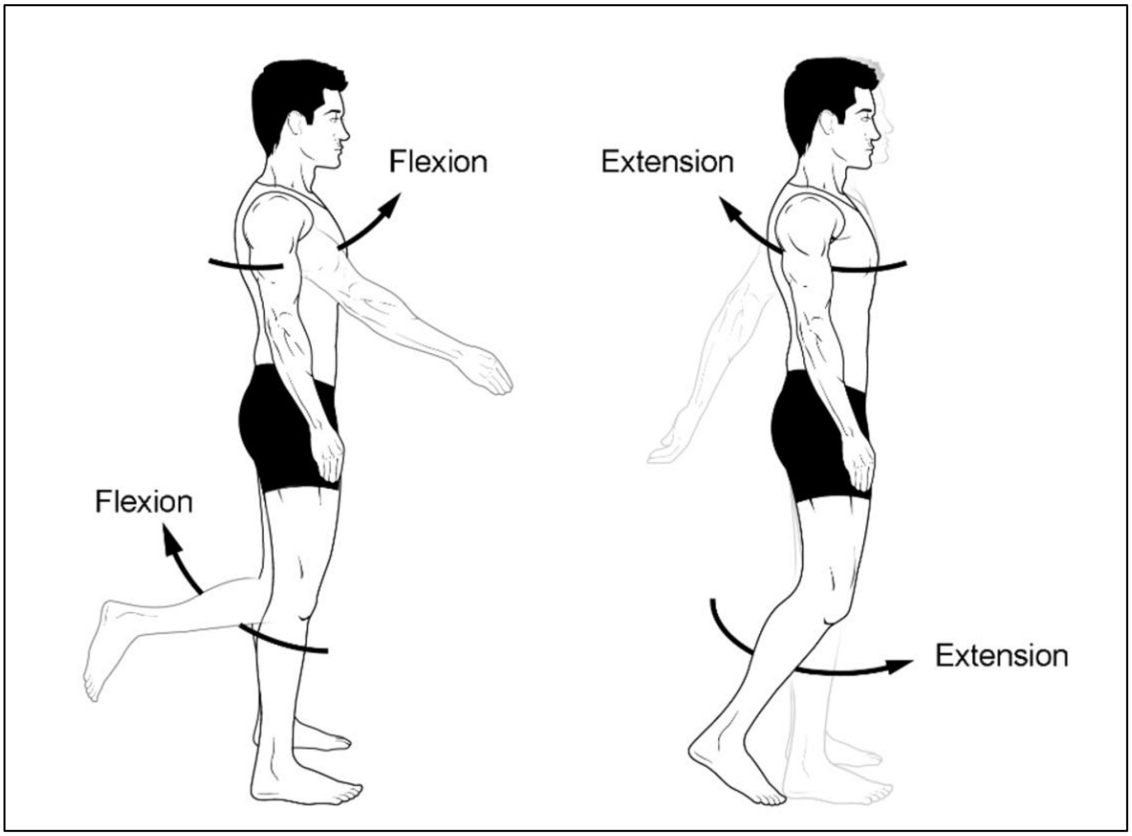


**Figure 8:** Flexion vs. extension (Gordon Betts et al., 2013).

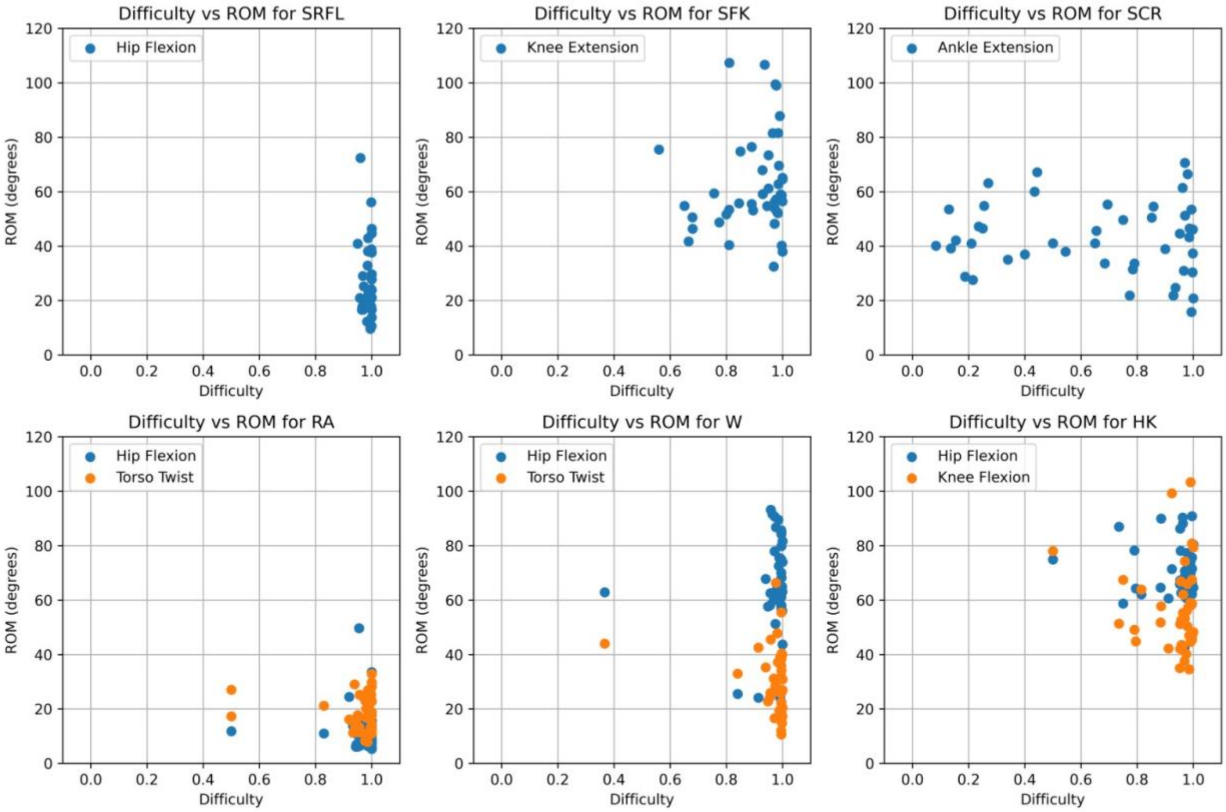


**Figure 9**: Difficulty vs ROM for each *(n*=11) for each ZEST-E exercise. RF: Seated Reach Forward; KE: Seated Knee Extension; CR: Seated Calf Raise; RA: Standing Reach Across; W: Standing Windmills; HK: Standing High Knees.

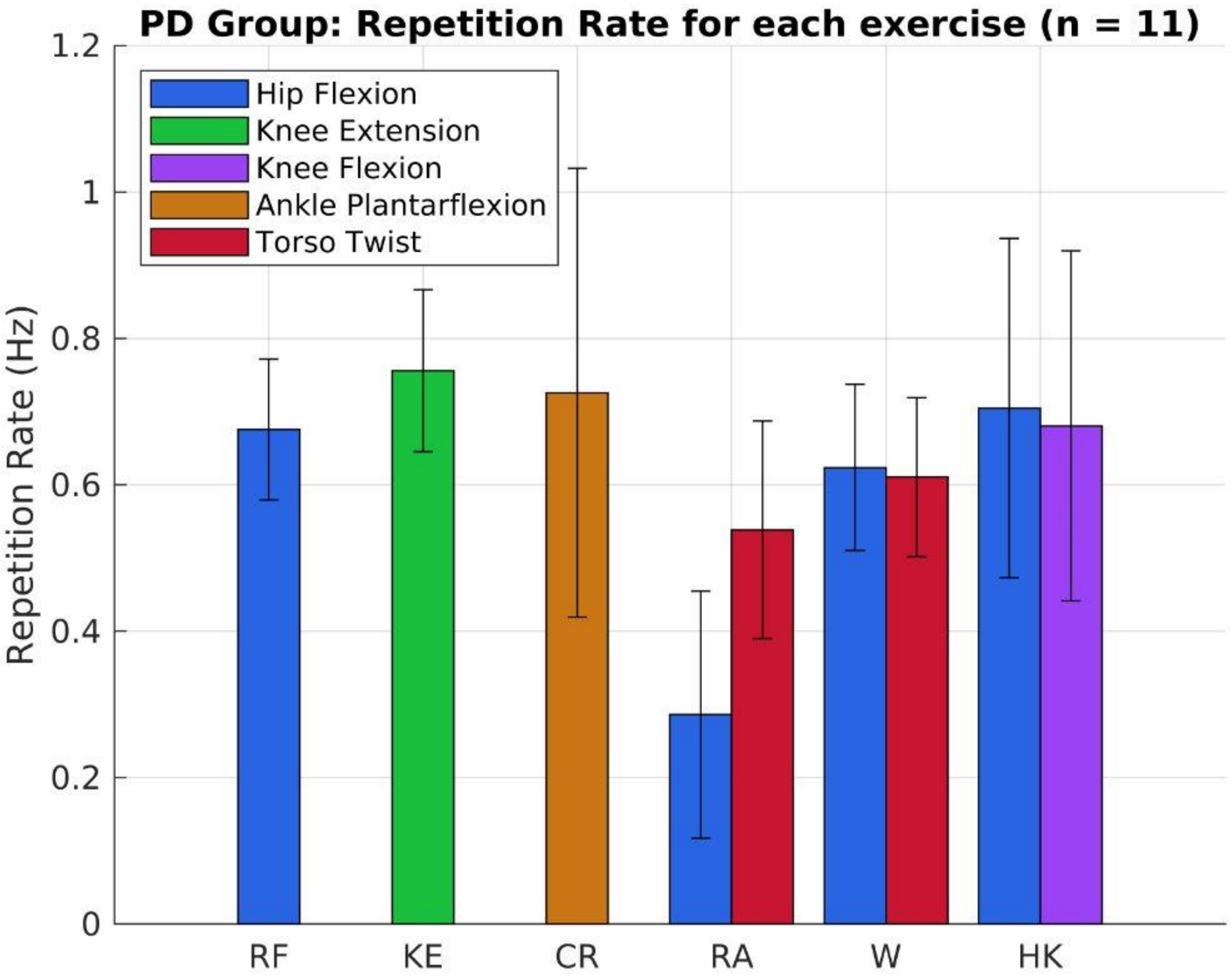


**Figure 10:** RR achieved by PWP *(n*=11) for each ZEST-E exercise. RF: Seated Reach Forward; KE: Seated Knee Extension; CR: Seated Calf Raise; RA: Standing Reach Across; W: Standing Windmills; HK: Standing High Knees.

| Exercise | Joint | RR (Hz) |
|---|---|---|
| Seated Forward Reach | Hip Flexion | 0.676 ± 0.096 |
| Seated Knee Extension | Knee Extension | 0.756 ± 0.111 |
| Seated Calf Raises | Ankle Plantarflexion | 0.726 ± 0.307 |
| Standing Reach Across | Hip Flexion | 0.286 ± 0.169 |
| Standing Reach Across | Torso Twist | 0.539 ± 0.149 |
| Standing Windmills | Hip Flexion | 0.624 ± 0.114 |
| Standing Windmills | Torso Twist | 0.611 ± 0.109 |
| Standing High Knees | Hip Flexion | 0.705 ± 0.232 |
| Standing High Knees | Knee Flexion | 0.681 ± 0.239 |

**Table 4.** RR data

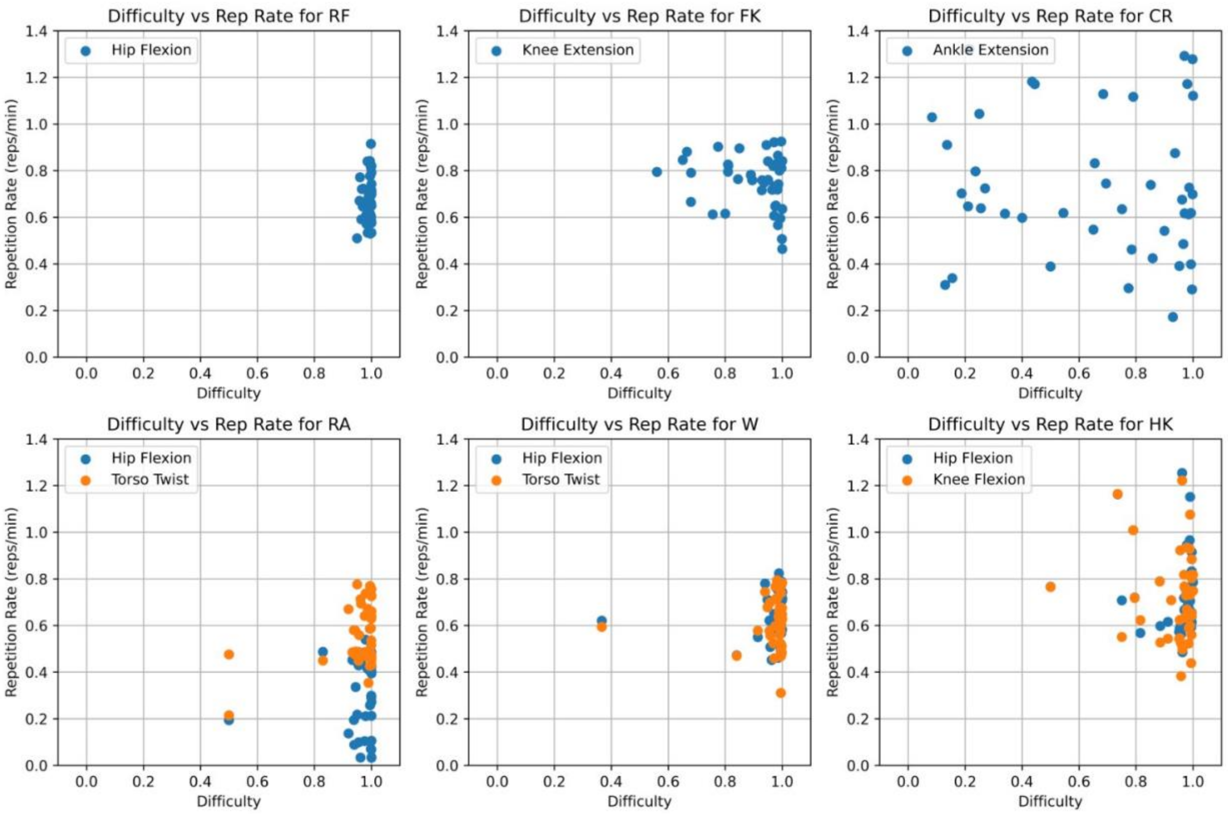


**Figure 11**: Difficulty vs RR for each *(n*=11) for each ZEST-E exercise. RF: Seated Reach Forward; KE: Seated Knee Extension; CR: Seated Calf Raise; RA: Standing Reach Across; W: Standing Windmills; HK: Standing High Knees.

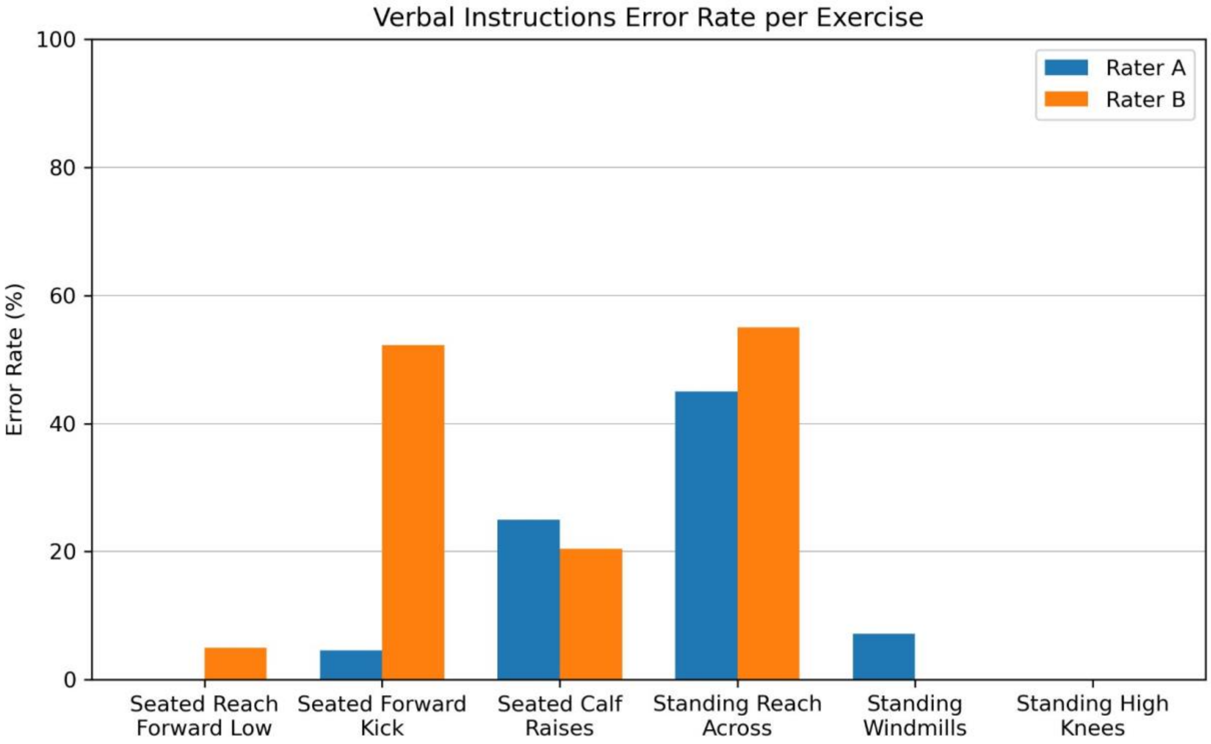


**Figure 12:** Verbal instructions error rate per exercise according to physical therapists.

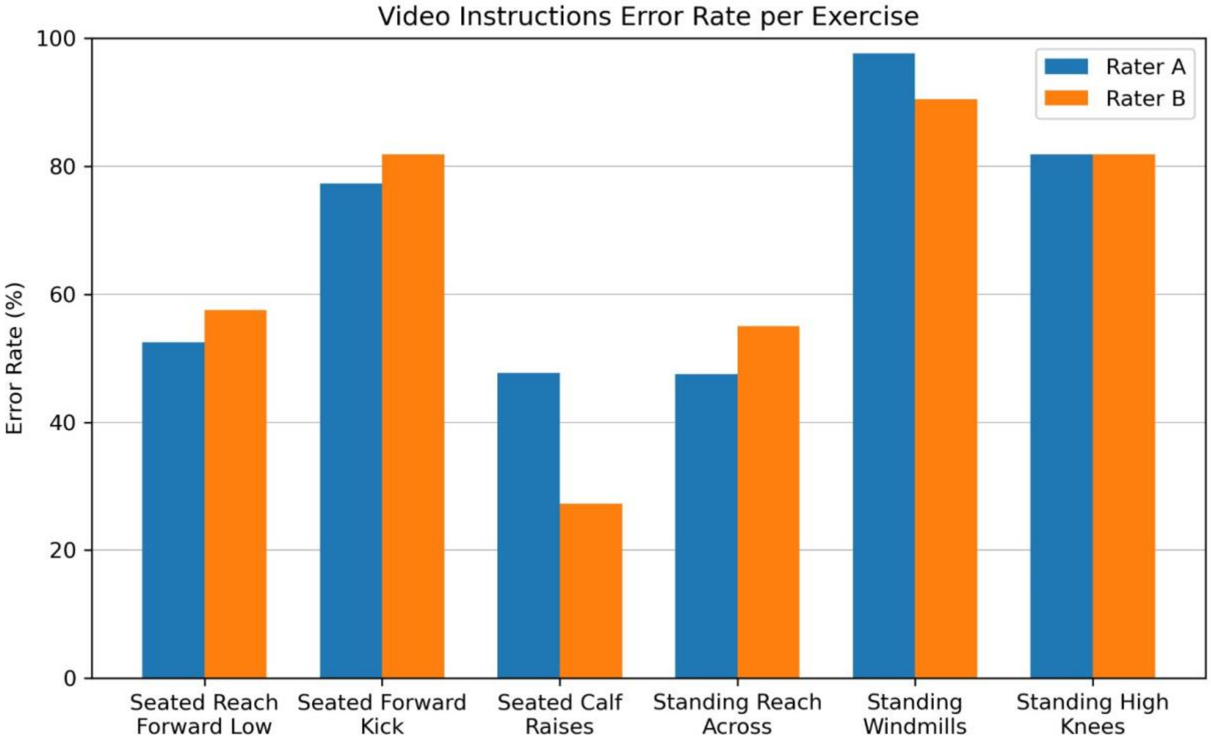


**Figure 13:** Video instructions error rate per exercise according to physical therapists.

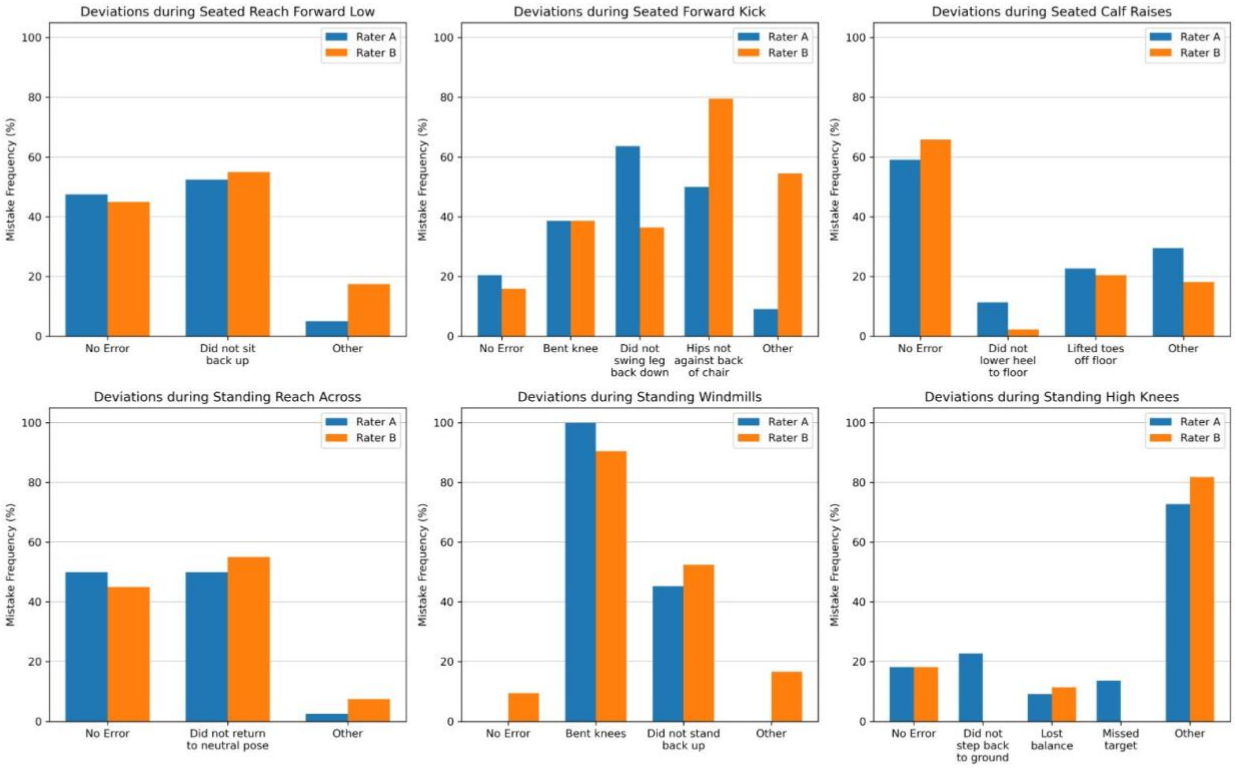


**Figure 14:** Exercise deviations type according to physical therapists.

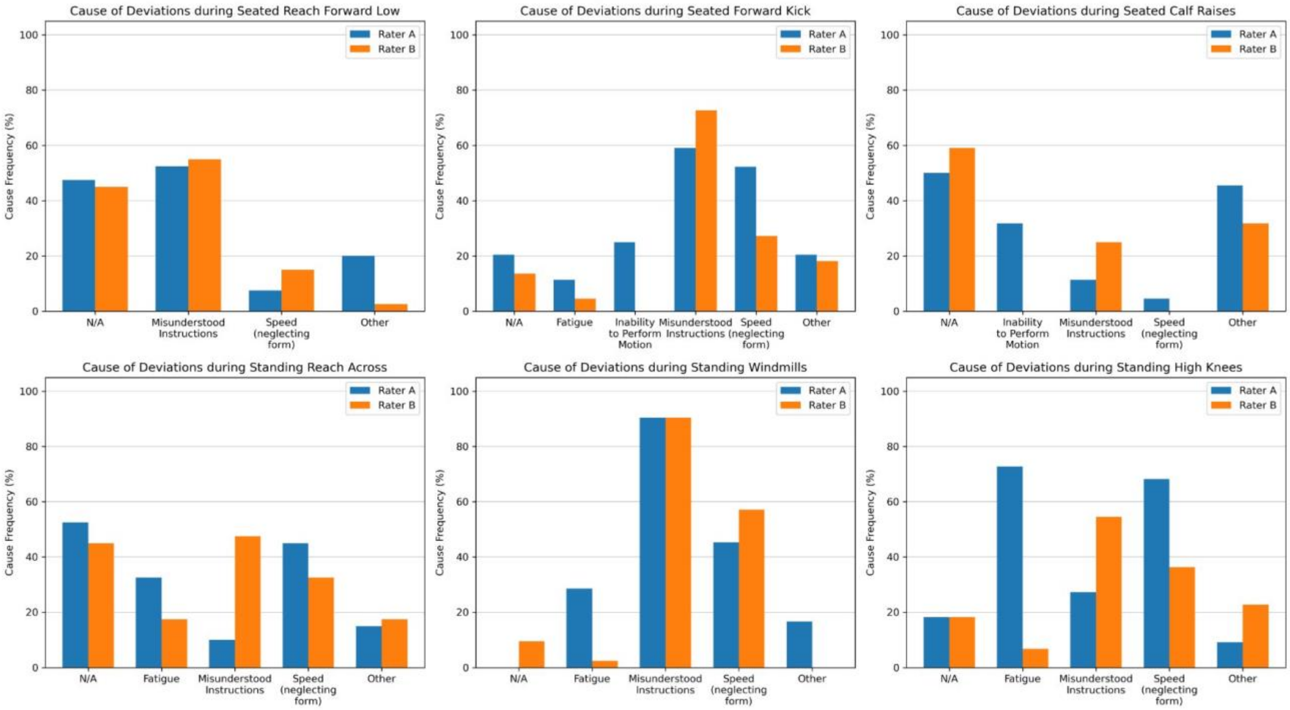


**Figure 15:** Hypothesized cause of deviations according to physical therapists.

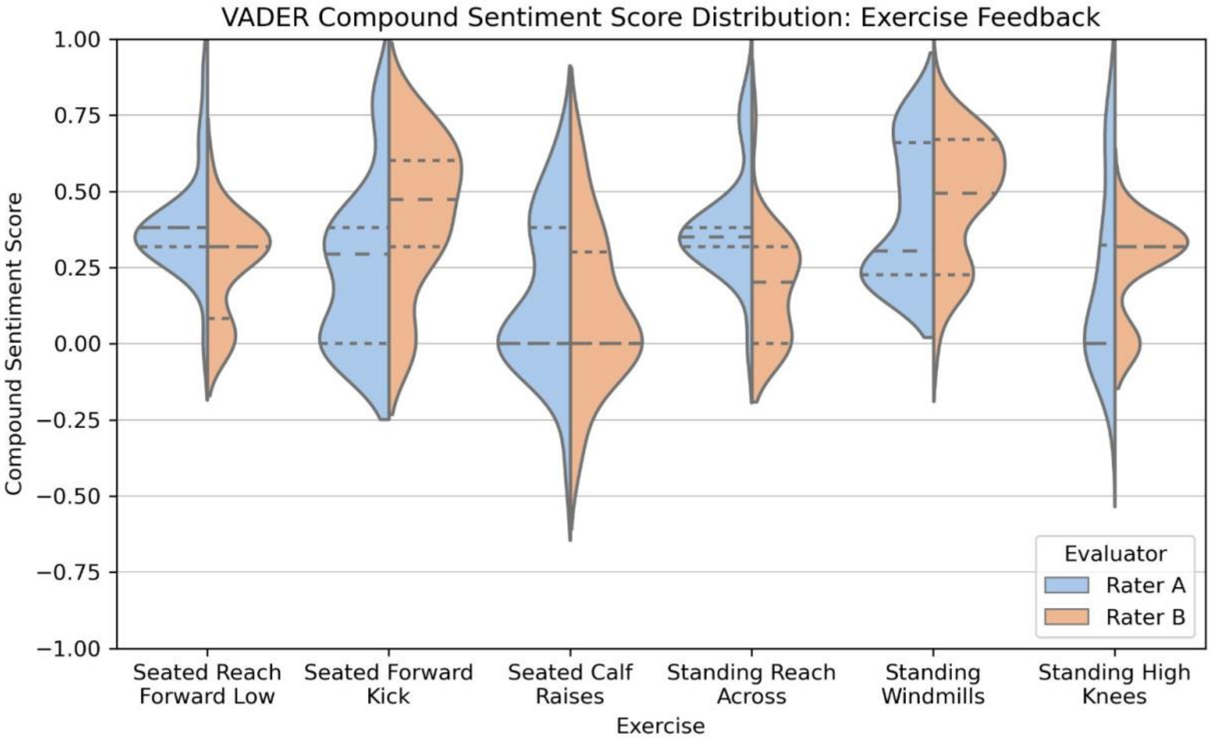


**Figure 16:** VADER Compound Sentiment Score Distribution: Exercise Feedback.

| Exercise | K – Verbal | Verbal Interpretation | K – Video | Video Interpretation |
|---|---|---|---|---|
| Seated Reach Forward Low | 0.87 | Almost perfect agreement | 0.89 | Almost perfect agreement |
| Seated Forward Kick | 0.18 | None to slight agreement | 0.77 | Substantial agreement |
| Seated Calf Raises | 0.66 | Substantial agreement | 0.56 | Moderate agreement |
| Standing Reach Across | 0.89 | Almost perfect agreement | 0.92 | Almost perfect agreement |
| Standing Windmills | 0.78 | Substantial agreement | 0.80 | Substantial agreement |
| Standing High Knees | 1.00 | Almost perfect agreement | 0.68 | Substantial agreement |

**Table 5:** Instruction adherence interrater reliability Cohen's Kappa (K). "Cohen suggested the Kappa result be interpreted as follows: values ≤ 0 as indicating no agreement and 0.01–0.20 as none to slight, 0.21–0.40 as fair, 0.41– 0.60 as moderate, 0.61–0.80 as substantial, and 0.81–1.00 as almost perfect agreement" (McHugh, 2012).

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