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An Exploration of Robot-Mediated Tai Chi Exercise for Older Adults

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Featured Application: This study demonstrates the feasibility of robot-mediated Tai Chi exercise for older adults, foundational information to guide future robot tutor design, and a comparison baseline to evaluate the effects of robot-mediated exercise.

Abstract: In this fast-aging society, many older adults fail to meet the required level of exercise due to trainer shortages. Therefore, we developed a robot tutor to investigate the feasibility of robot-mediated exercise for older adults. Twenty older adults participated in an experimental study. A pre-exercise survey was used to assess their background. Each participant experienced a 30-min robot-led Tai Chi exercise followed by a post-exercise survey to evaluate the easiness of following the robot and expectations for future robot design. Participants' Tai Chi performances were evaluated in terms of completion and accuracy. Associations between the surveys and the performance were also analyzed. All participants completed the study. Fifteen out of the twenty subjects had at least one chronic condition, and most practiced Tai Chi before the study but had never interacted with a robot. On average, the participants scored 93.09 and 85.21 out of 100 for movement completion and accuracy, respectively. Their initial movement accuracy was correlated with their attitude towards exercise. Most subjects reported that they could follow the robot's movements and speeches well and were interested in using a robot tutor in the community. The study demonstrated the initial feasibility of robot-led Tai Chi exercise for older adults.

Keywords: older adults; Tai Chi; robot-mediated exercise

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1. Introduction

According to the United States Census Bureau's reports, there were 54.1 million people aged 65 and older in 2019 (16% of the U.S. population), up from 39.6 million in 2009 [1]. This population is fast-growing and expected to reach 80.8 million by 2040 and 94.7 million by 2060 [2]. With such an increase in this population, promoting healthy aging has become one of the key agendas in the U.S. Regular exercise promotes both physical and cognitive function, and thus is essential for healthy aging and offers a range of health benefits, such as the reduced risk of all-cause mortality, chronic disease, and premature death [3,4]. However, research shows that one of the main reasons older adults fail to meet the required level of exercise is the lack of knowledge and guidance offered by exercise trainers or tutors [5–7].

Having a human instructor for each older individual is infeasible considering the fast-growing trend of this population. Technologies have been investigated to address this bottleneck. Humanoid robots are being designed to promote healthy lifestyles [8] for older adults, such as serving as companions [9–11] and therapeutic/intervention tools [12–16]. Compared to a screen-based agent, users tend to enjoy spending time with robots and find the interaction helpful and useful [17], which may be due to the physical embodiment of the robot that enables a better social connection with users [18]. Literature reveals that the humanlike appearance of the robot to communicate, initiate interaction, and foster positive reactions to meet the personalized needs of users is essential to the acceptance and the efficacy of robot-mediated interventions for older adults [19,20]. Some older adults expressed that they may not need a robot in the present but consider it to be potentially useful in later years when they suffer from frailty, loneliness, and disability [21].

Therefore, emerging research is investigating the feasibility of using robots to deliver physical and cognitive interventions to older adults, such as supporting social and cognitive stimulation for older adults with mild cognitive impairments [22,23]. However, most current studies focus on simple verbal emotional and communicational supports with very simple body motion [15,24] (e.g., head nodding and pointing using an arm), while the robots' capability of demonstrating more complex body movements has not been fully taken advantage of. In this study, we designed a robot tutor focusing on instructing Tai Chi (organized full-body motions) and conducted an exploratory experiment to understand if older adults (age $\geq$ 65 years) can follow the robot.

Tai Chi [25] is a gentle aerobic exercise that involves the learning of choreographed movement patterns, which helps improve physical health (e.g., strength and balance), cognitive function (e.g., visuospatial processing) [26], mental health (e.g., depression, stress) [27], and self-efficacy [28]. Tai Chi has been practiced for a long time in the East and is gaining increasing popularity in the West [29]. It is relatively nonstrenuous, low impact, and is characterized by postural alignment, weight shifting, and relaxed circular movements [30]. Tai Chi also promotes attentional focus and memory through learning the choreographed movements in sequence [31], which may have an additive effect on brain health [32].

Commercial humanoid robots have the physical capability of demonstrating Tai Chi movements and verbally explaining them [33,34]. However, there has been no study that investigated the feasibility of conducting a robot-led Tai Chi exercise for older adults. Considering the promising benefits of practicing Tai Chi and older adults' high acceptance of interacting with a humanoid robot, it is important to fill this research gap, which will be a critical step towards providing effective technology-driven exercise for older adults who do not have enough resources to participate in traditional human-led sessions.

Therefore, the purpose of this study is to examine the preliminary feasibility of using a humanoid robot tutor to lead Tai Chi exercise for older adults. We developed a robotic Tai Chi tutor that could demonstrate Tai Chi body movements and verbally explain them. A preliminary user study with 20 older adults was conducted to investigate whether they could understand and follow the robot, their performance, and their expectations for future robot tutor development and applications. This work provides a foundation and evidence to support further pilot studies with a larger sample size and control groups.

The robot tutor design, experimental protocol, participants, study results, and data analyses are detailed in the following sections, followed by a discussion on the implication of the findings, especially on the interpretation of the results and the future robot system design.

2. Materials and Methods

2.1. Apparatus

2.1.1. Robot Tai Chi Tutor Development

The robot tutor was developed using a programmable humanoid robot, NAO (Figure 1, left) [35]. It is 58 cm-tall and weighs 11 lbs. Its size and weight allow users to see its movement clearly without feeling intimidated. NAO has 25 degrees of freedom and can smoothly move its body parts. It also has two speakers and a text-to-speech engine that allows the robot to speak designed scripts in a gender-neutral robotic voice. For over a decade, NAO has been widely applied for older adult–robot interaction studies due to its attractive humanoid appearance, high controllability, and robustness [36,37]. These studies mainly include social interaction [15], simple physical training [38], psychological well-being [39], and cognitive training [22]. NAO's mechanical and electrical functions enable it to perform Tai Chi movements well [33,34].

Figure 1. NAO robot (**left**) and skeleton tracking (**right**; not a participant, for demonstration only, with permission).

We designed six movements based on elemental postures in the Yang Style 24-Posture Short Form [40]. Considering the participants' age, only postures with low levels of difficulty that require a limited range of stretch, moderate limb strength, and easy balance were selected. Each movement started and ended by slightly separating the two feet and evenly distributing the body weight between the two feet. Some movements were also modified for safety, such as the "Ma Bu", which is similar to a squat, and "Sideway Stepping", which resembles a side squat, were reduced to a third to a half of the original range. More detailed information about each movement is described in Figure 2.

Although NAO has been one of the best humanoid robots on the market, its balancing and stepping are not as stable as those of a human, so we did not include continuous stepping and turning. The robot does not have a waist joint, and thus motions with waist turn were not included, either.

All robot movements were first designed, configured, and adjusted using the Choregraphe software (version 2.8.5) to ensure correct posture positions, balance, and motion ranges. Then, the movements were converted as robot dynamic parameters and programmed into a robot control program powered by the Naoqi Python API (version 2.5). We further adjusted the smoothness and speed of the motions. These were examined and approved by a certified Tai Chi instructor. A set of scripts were designed to verbally explain the movements. The text-to-speech engine of the robot was used for the robot to speak out those explanations. The speech engine and the motion control were designed to work in parallel so that the robot's movements and speeches were synthesized and coordinated, enabling the robot to demonstrate movements along with simultaneous verbal instructions, as would be performed by a human tutor.

2.1.2. System Setup for the Study

The study was arranged in a research laboratory, as illustrated in Figure 3. The robot was standing on a table (36 inches high) so the participant could see the full body of the robot. The participant and the robot were 2–3 m apart. Two webcams recorded the full-body movements of the participants from a frontal view and a side view, respectively. An Orbbec Astra camera [41] was placed beside the frontal view webcam to record the full-body movements of the participants (Figure 1, right). The Orbbec camera could track the position of 19 skeleton joints that outline the posture of the participant at a speed of 30 frames per second.

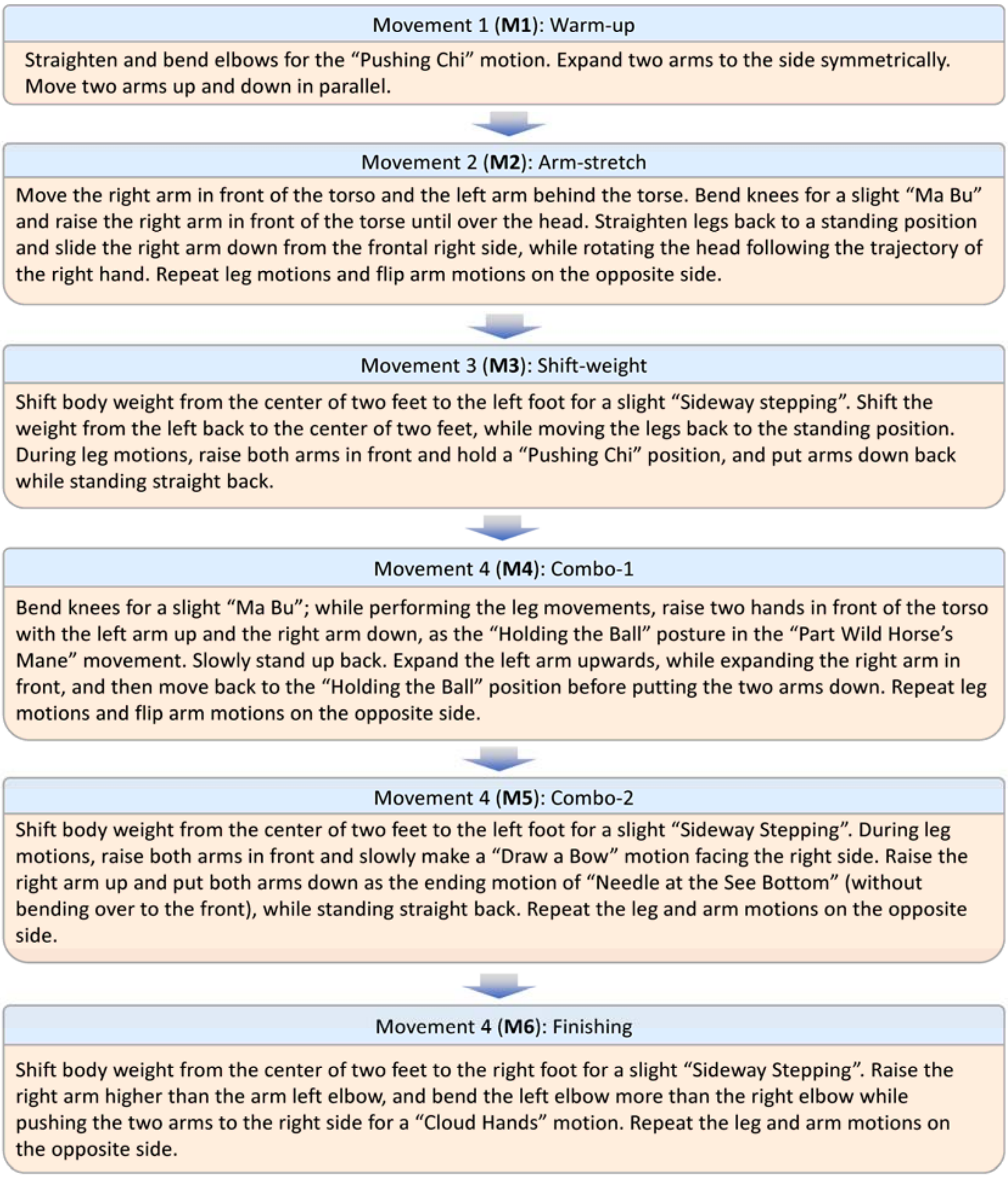

Figure 2. Six Tai Chi movements for the study.

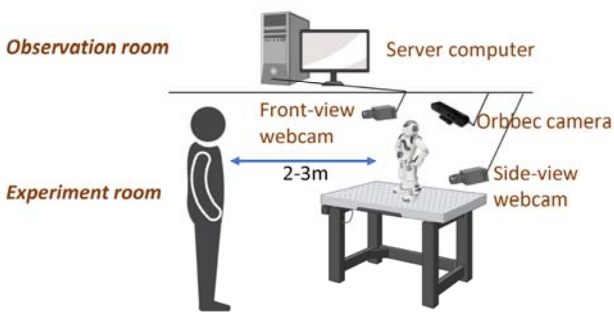

Figure 3. Study room settings (Figure created with BioRender.com).

2.2. Study Design and Measurements

2.2.1. Study Design and Ethics Statement

This study was conducted using a single-group experimental design, including a pre-exercise survey, a 30-min Tai Chi exercise mediated by the robot including two 2-min breaks, and a post-exercise survey. This study was approved by the Institutional Review Board (IRB) of the University of Wisconsin-Milwaukee (IRB #: 19.074). Informed written consent was obtained from each participant. Researchers thoroughly explained the study to the participants to ensure they understood the entire process of the session.

2.2.2. Participants

Recruitment flyers were distributed in local communities in the city of Milwaukee, Wisconsin, U.S. To qualify for the study, participants were required to be 65 years or older and understand English. Potential participants would be excluded if they had severe functional limitations (e.g., need to use a wheelchair, crutches, walkers, etc.) and severe cognitive impairment (e.g., Alzheimer's disease and related dementias) that prevented them from performing mild–moderate physical activities, such as walking and slow dancing. Participants were recruited first-come, first-served.

2.2.3. Pre-Exercise Survey

This survey collected participants' demographic information, current health conditions, experience with and attitude toward physical exercise (including Tai Chi), and experience with assistive technology (e.g., Alexa and motorized walkers) and robots. Multiple selection, open-ended, and Likert scale (from 0 (not at all) to 9 (very much)) questions, as summarized in Figure 4, were used.

Basic Demographic Information	
Q1. Race/ethnicity, age, gender identification.	
Q2. Health condition (e.g., cardiovascular conditions, arthritis) identification.	Multi-selection
Q3. Number of people in the household.	Open-ended

Exercise and Tai Chi Experience	
Q4. Current physical exercise experience.	Open-ended
Q5. Current physical exercise frequency.	Open-ended
Q6. Tai Chi experience.	Open-ended
Q7. How important do you consider exercise in your life?	Likert-scale

Technology Experience	
Q8. Assistive technology usage experience.	Open-ended
Q9. Experience with robots.	Open-ended

Figure 4. Pre-exercise survey questions.

2.2.4. Robot-Mediated Tai Chi

After the pre-exercise survey, each participant practiced Tai Chi for about 30 min following the robot. The participants were told that safety and comfort were the priorities and to not follow a movement if that might interfere with their balance or if it felt uncomfortable. To engage the participant, the robot greeted and introduced itself before demonstrating Tai Chi. Then, it instructed the participant to follow its movements and explanations. The robot demonstrated the movements listed in Figure 2 one-by-one. Each movement was instructed following a "whole movement–structured decomposition–whole movement" sequence, as shown in Figure 5.

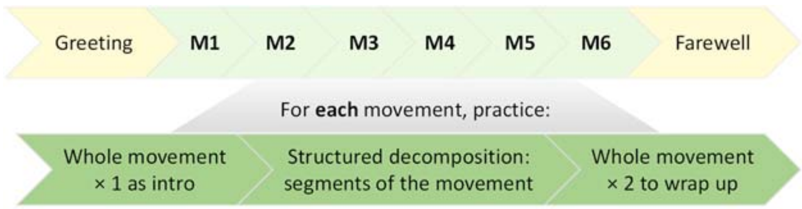

Figure 5. Tai Chi exercise flow.

First, the robot demonstrated the whole movement. Then, the movement was broken down into a few segments, and the robot guided the participant through each segment one-by-one to emphasize details. After that, the robot linked all the segments together so the participant could practice the whole movement continuously. Finally, the whole sequence was practiced for the last time to conclude the practice for this movement. The robot explained all movements throughout. The whole exercise lasted for 30 min. The robot ended the session with salute postures (e.g., the traditional martial art "Palm Hold Fist") and praises (e.g., "You did a great job!"), followed by a farewell. Each participant had 64 movement pieces to perform, either whole movements or broken-down segments. Considering the length and difficulty level of the movements, two short breaks (1–2 min) were arranged after Shift-weight and Combo-2 movements to mitigate the mental and physical workload.

2.2.5. Post-Exercise Survey

The post-exercise survey consisted of 10 questions to assess: (1) the participants' perception of the robot, i.e., whether they could understand and follow the robot, (2) their attitude towards and expectations of the robot, and (3) their feedback regarding the exercise itself. After rating on each Likert scale from 0 (not at all) to 9 (very much), the participant could also further explain the rating. Figure 6 shows the details.

Perceptions (Understanding and Following) On the Robot.	
Q1. Could you understand the robot's speeches?	Likert-scale
Q2. Could you see the robot's postures clearly?	Likert-scale
Q3. Could you follow the postures of the robot?	Likert-scale
Attitude Towards the Robot.	
Q4. Would you like to have such a robot at home?	Likert-scale
Q5. Would you want the robot to understand your speeches?	Likert-scale
Q6. Would you want the robot to understand your postures?	Likert-scale
Q7. Would you want the robot to understand your facial expressions that show your emotions?	Likert-scale
Feedback On the Robotic Tai Chi Exercise	
Q8. What was the best part of the exercise?	Open-ended
Q9. What was the worst part of the exercise?	Open-ended
Q10. What improvement will make the robot-mediated exercise better?	Open-ended

Figure 6. Post-exercise survey questions.

2.3. Data Analysis

2.3.1. Tai Chi Performance: Video Coding and Analysis

Each movement was rated from 0 (worst) to 100 (best) for completion and accuracy through video coding, independently by two coders. Completion indicated how much of a movement the participant tried to follow, and accuracy indicated how correctly the participant moved during the imitated parts. Each movement piece was rated by two independent coders, and the average rate between the two coders was used as the final score.

As mentioned in the "system setup for the study" section, participants' body movements were recorded using cameras. Due to a software issue, the webcams did not record the last 1/3 of the Tai Chi session for 18 participants. Those were covered by the Orbbec 3D skeleton recording. The coders were provided a coding scheme as a rubric that detailed each movement and a video of the robot performing Tai Chi. The investigators met the coders to explain the coding scheme with examples and communicated with the coders in case there were any questions or confusion. For the webcam and the Orbbec recordings, the inter-rater agreement, in terms of whether a movement was imitated, was 97.7% and 83.5%, respectively. Since the Orbbec recording showed animated skeleton plots without the participant's appearance and background, the coding could be less intuitive and thus generate a lower agreement score. Out of the 1280 movement pieces (a whole form or its broken-down segments) to be performed (64 pieces $\times$ 20 participants), there were only 2 pieces (0.16%) that both coders considered were not performed, and 94 pieces (7.4%) that one coder considered not performed, respectively.

Participants' scores across all movements and all pieces (whole forms and segments) were used to evaluate the general performance. For each movement, participants' performance of the first and last whole form was compared to check progress.

2.3.2. Surveys

For the pre- and post-surveys, statistical and qualitative analyses were conducted for the Likert scales and verbal feedback, respectively. Associations between the participants' performance and the survey ratings were studied through correlation analysis.

2.3.3. Statistical Analysis

The Shapiro–Wilk test showed that most of the data distributions were not normal. Therefore, the non-parametric Wilcoxon signed-rank test was applied to determine the significance of evaluating performance differences. The non-parametric Spearman's rank correlation coefficient (r_s) was applied, where $0 \leq r_s < 0.4$, $0.4 \leq r_s < 0.6$, and $r_s \geq 0.6$ mark the ranges of weak, moderate, and strong correlations, respectively. Statistical significance was considered as a p-value < 0.05. All analyses were conducted using MATLAB (version R2019b).

3. Results

3.1. Participants' Characteristics and Experiences (from the Pre-Exercise Survey)

As shown in Table 1, 20 qualified older adults (average age: 70.30 years, SD: 3.76 years, range: 65–78 years) participated, including 13 females and 7 males, 19 Caucasian and 1 Latino. From the pre-exercise survey, 15 out of the 20 participants (75%) reported existing health conditions, including hypertension, high cholesterol, heart and vascular diseases (e.g., stroke, heart attack, angina, etc.), respiratory problems (e.g., asthma, COPD, etc.), arthritis, and overweight/obesity. The most common conditions were cardiovascular diseases (n = 7, 35%), respiratory problems (n = 7, 35%), and overweight/obesity (n = 6, 30%). Eight participants (40%) lived alone, and the others (60%) had two people in the household.

Table 1. Summary of participants' baseline characteristics and comorbidities (n = 20).

Characteristics		Average/Frequency (SD, Range)
Age (Year)		70.30 (3.76, 65–78)
Gender	Male	7
	Female	13
Health conditions	Cardiovascular disease	7
	Respiratory disease	7
	Overweight/obesity	6
Number of people in the household (including the subject)	Alone	8
	Two	12

On average, the participants rated 8.45 out of 9 for the importance of exercise in their life, mostly for maintaining health, well-being, and independence. The most common exercises were walking (n = 15, 75%), weight curls (n = 5, 25%), and biking (n = 5, 25%). For Tai Chi experience, 2 (10%) were actively practicing, 11 (55%) had practiced in the past (decades to months ago), and 7 (35%) had no previous experience. Thirteen participants (65%) exercised three to seven times/week, while the others (n = 7, 35%) exercised less. Only two participants had used assistive technology such as Alexa, and only one participant had interacted with a robot.

3.2. Exercise Performance

Table 2 shows the statistics for movement completion. In four out of the six movements, the participants achieved better completion in the last whole movement. This change in M2, M4, and M6 was significant. M1 (warm-up) was rated 100 in both the first and the last whole movement. This was expected as the warm-up was designed to be simple. M5 significantly decreased. A possible reason was that M5 was the longest and most challenging due to the combination of weight-shifting and multiple arm motions, which might cause fatigue after repetitions.

Table 2. Wilcoxon signed-rank test results on participants' movement completion scores.

Movement	First Whole Movement, Mean (SD)	Last Whole Movement, Mean (SD)	Z	*p*
M1. Warm-up	100 (0)	100 (0)	0	1.00
M2. Arm-stretch	***85.67 (26.07)***	***98.50 (1.83)***	**−2.05**	**0.04 ***
M3. Shift-weight	95.95 (6.73)	98 (4.02)	−0.98	0.33
M4. Combo-1	***84.28 (29.61)***	***99.13 (2.72)***	**−1.96**	**0.0498 ***
M5. Combo-2	*90.34 (17.68)*	*65.88 (25.51)*	*2.66*	*<0.01 **
M6. Finishing	**75.75 (25.25)**	**93.25 (15.92)**	**−2.19**	**0.03 ***

* Statistical significance.

Table 3 shows the statistics for movement accuracy. Similar to movement completion, in four out of the six movements, the participants achieved better accuracy in the last whole movement than in the first whole movement. This improvement in M2, M3, and M4 was significant. As previously mentioned, M1, the warm-up, was scored at almost 100, as it was designed to be simple. M3 and M5 significantly decreased, which was aligned with the observation in movement completion that shifting weight was challenging and adding arm motions might cause even more fatigue after repeated practice.

Table 3. Wilcoxon singed-rank test results on participants' movement accuracy scores.

Movement	First Whole Movement, Mean (SD)	Last Whole Movement, Mean (SD)	Z	*p*
M1. Warm-up	98.85 (2.45)	99.65 (0.78)	−1.56	0.12
M2. Arm-stretch	***85.03 (14.74)***	***94.20 (5.39)***	**−3.28**	**<0.01 ***
M3. Shift-weight	*95.98 (4.95)*	*92.40 (6.93)*	*3.13*	*<0.01 **
M4. Combo-1	***79.05 (23.08)***	***90.53 (9.43)***	**−2.20**	**0.03 ***
M5. Combo-2	*81.63 (14.76)*	*57.93 (18.09)*	*3.10*	*<0.01 **
M6. Finishing	**55.65 (22.73)**	**72.45 (16.27)**	**−2.44**	**0.01 ***

* Statistical significance.

3.3. Participants' Experience of the Robot-Led Tai Chi Exercise (from the Post-Exercise Survey)

3.3.1. Perceptions of the Robot

The participants rated 7.85 out of 9 (SD = 1.63) for question 1 ("Could you understand the robot's speeches?"), indicating that the robot's speeches were well-understood. From the qualitative feedback, the most common comment was that the robot spoke slowly and clearly, which facilitated understanding. Meanwhile, they also noted that the robot had an accent (robotic voice). Therefore, occasionally, the participants could not understand words and match them with the movements. Question 2 (“Could you see the robot’s postures clearly?”) received an average rating of 7.70 (SD = 1.22), indicating that the robot’s postures were clearly perceived. They also noticed the difference between the robot’s body structure (e.g., length ratios and joint motions) and that of a human, and thus some postures may appear distorted. Accordingly, they rated an average of 6.55 (SD = 1.70) for question 3 (“Could you follow the postures of the robot?”), showing that they could follow the robot’s postures in general, but encountered some difficulties and confusion. The most important factor was that the participants were confused about whether to mirror the robot’s postures when facing it (the robot’s right corresponded to the participant’s left, and vice versa) or perform the same side as instructed verbally by the robot (the robot’s right/left corresponded to the participant’s right/left). The robot could not accommodate the participants in terms of changing the performing side. Meanwhile, participants pointed out that the movement breakdowns and repeats were helpful.

3.3.2. Attitude toward the Robot and Future Expectations

On average, the participants rated 5.75 (SD = 3.40) for question 4 (“Would you like to have such a robot at home?”), showing modest acceptance, with a common reason being seeking “a fun experience”, while many others emphasized the preference for a community-based, interactive, or socializing experience instead of at-home exercise.

The average ratings for questions 5 (“Would you want the robot to understand your speech?”) and 6 (“Would you want the robot to understand your postures?”) were 6.85 (SD = 2.91) and 7.65 (SD = 1.60), respectively. Participants hoped that the robot could personalize the exercise (e.g., repeating a posture as needed) and give real-time feedback (e.g., correcting a gesture and pointing out how to improve) if the robot could understand their speech and postures. Participants only rated 5.4 (SD = 3.10) on question 7 (“Would you want the robot to understand your facial expressions that show your emotions?”). Some participants thought this would help the robot identify their confusion, while most people felt it unnecessary or showed concerns (e.g., “might creep me out”).

3.3.3. Feedback Regarding the Robotic Tai Chi

All subjects gave positive feedback for question 8 (“What was the best part of the exercise?”), and most said the session was a fun experience and appreciated practicing the gentle, comfortable, and calming motions with soothing music. For questions 9 (“What was the worst part of the exercise?”) and 10 (“What improvement will make the robot-mediated exercise better?”), the most common feedback was on the confusion about whether to mirror the robot’s sides, which aligned with the feedback for question 3 (“Could you follow the postures of the robot?”). A few participants also reported that some postures were challenging, and that the robot’s motion was unnatural, which aligned with the feedback regarding the difference between the robot’s and a human’s body structure (question 2). Some participants mentioned individual preferences, such as skipping the breaks, rearranging the movement breakdowns, and making the robot more intelligent, which aligned with the feedback regarding making the robot understand the user’s speech and postures (questions 5 and 6).

3.4. Association between Tai Chi Performance and Survey Ratings

To understand if there was any association between the participants’ Tai Chi performance and their background, perceptions, and attitude, we conducted correlation analyses between the performance scores and the survey ratings.

Results showed no significant correlation between performance and age. There was no significant correlation between movement completion and survey ratings. The only significant correlation between accuracy and the survey rating was on question 7 (“How important do you consider exercise in your life?”) in the pre-exercise survey. Participants’ perceptions of the importance of exercise were strongly correlated with the first whole movement accuracy ($r_s(18) = 0.63$, $p < 0.01$), which indicated that participants who tended to acknowledge the importance of exercise were able to accurately perform a new movement.

4. Discussion

4.1. Main Findings

Overall, the study results showed that participants could follow the robot-mediated Tai Chi program well, despite the physical conditions reported, which are common in their age group (e.g., cardiovascular diseases and respiratory problems). However, it should be noted that none of the participants reported cognitive impairments, which could have decreased the participants' performance and experience with the Tai Chi program, considering mild cognitive impairment impacts about 20% of older adults in the U.S. [42]. Specifically, M3 (weight-shifting) and M5 (weight-shifting + a few complex arm motions) appeared to be more challenging than other movements included in our program. While participants' performance increased from the beginning (the first whole movement demonstration) to the end (the last whole movement demonstration) in most movements, it decreased in M3 and M5, possibly due to the high level of complexity and leg strength required, which seemed to cause more fatigue. Therefore, various forms of Tai Chi should be carefully considered to accommodate the needs and capabilities of different users (e.g., wheelchair Tai Chi for older adults who need to use walkers and wheelchairs) [43] when developing a robot-mediated Tai Chi program.

4.2. Participants' Recommendations and the Corresponding Implications

Participants provided thoughtful feedback on future robot design. They hoped the robot could understand, support, and improve their Tai Chi performance. This requires a comprehensive gesture cognition method that not only evaluates posture accuracy but also identifies ways to improve and adapt. Traditional numerical accuracies [44] would not help the user understand how to improve; instead, verbal explanation and motion demonstrations to facilitate understanding are essential. Many participants hoped to use a robot tutor at a community center, where group exercise is more common than individual training. This poses a challenge to the robot's ability to capture each participant's movement and give individual feedback. A careful balance needs to be kept between providing valuable feedback, controlling the pace of exercise, and maintaining social appropriation.

The participants either lived alone or with only one partner; however, most of them did not show an interest in having a robot at home, with many preferring to use it in the community. This aligns with previous research showing that older adults would love to use socially assistive robots as a facilitator to communicate with other people [45]. This expectation also demonstrated the need to design an easy robot control interface. At a community center, we cannot expect the staff to know robot control as well as researchers in lab studies. Therefore, a user-friendly interface should be developed for staff to run the robot as easily as using other common technologies, such as projectors and Bluetooth speakers.

4.3. Limitations and Future Works

While our findings provide insight into using humanoid robots as exercise tutors for older adults, we need to acknowledge a few limitations and important future works to strengthen the discovery. First, since the NAO robot has limited balancing capability and does not have a waist joint, it could not perform continuous stepping and turning. Therefore, these motions were not included in the robotic Tai Chi. Consequently, the positive feedback from the participants had excluded the potential effect of these difficult motions. Second, this study was conducted in a lab environment for individual participants. The feasibility of a robot tutor should be tested in a community setting with groups of older adults. Third, the study solely included older participants without any significant functional limitations and/or without cognitive impairment. Therefore, a relevant proportion of the older populations, such as those with multimorbidity, mobility restrictions, or cognitive impairment, was not considered. Thus, the results of this study were not representative of the entire population of older adults. In addition, Tai Chi has consistently shown benefits in reducing physiological fall risk [46], improving health [26,27], and improving the quality of life [28]. The current work had a small sample size (n = 20) and did not access these outcomes. Future pilot studies with a randomized clinical trials design and a powered sample size are necessary to validate the robot tutor in comparison with a real human tutor, likely through multi-session/longitudinal experiments. There has been no socially assistive robot that can outperform a real human. However, due to the limited availability of human tutors, if robot tutors can bring considerable health outcomes, they may prove to still be quite valuable and cost-effective (considering many users can share a robot). Finally, standard instruments should be applied to evaluate physical and cognitive functions as part of the screening process for more rigorous research.

5. Conclusions

This work investigated the feasibility of using a robot tutor to guide older adults through Tai Chi exercises. Results showed that older adults with self-reported common physical conditions and no cognitive impairments could follow the robot well. Most of the participants acknowledged the importance of exercise but had not used assistive technology and robots before the study. The participants performed well in general. After the exercise, the participants gave positive comments on the experience and provided important information regarding future robot design, such as hoping the robot could help to correct postures and be used in a community setting. Future robot tutor design to match the participants' expectations was also discussed.

Author Contributions: Z.Z. led the design of the overall research strategy, the experimental system, and the human subject study, conducted detailed data analyses, and led the manuscript composition. H.O. led the design of the Tai Chi movements, led the design of the study protocol and surveys, participated in raw data organization and metadata analyses, and contributed to the initial manuscript composition. M.M. developed and refined the experiment system, conducted the human subject study, and participated in the initial raw data organization. W.C. and Y.L. participated in the research strategy design, conducted metadata analyses, and contributed to the initial manuscript composition. All authors have read and agreed to the published version of the manuscript.

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