

Effects of a Mixed Reality-Based Physical Therapy Program on Muscle Thickness, Balance Confidence, Activities of Daily Living, and Quality of Life in Older Adults With Sarcopenia: A Preliminary Randomized Controlled Trial

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Abstract

Background: Older adults with sarcopenia often engage in therapeutic exercises to improve muscle thickness, balance confidence, activities of daily living (ADL), and quality of life (QOL). However, conventional face-to-face group exercise programs are typically standardized. This study aimed to evaluate the effects of a Mixed Reality–based Physical Therapy platform (Mr.PT) compared with Conventional Physical Activity (CPA) programs on quadriceps muscle thickness, balance confidence, independence in ADLs, and quality of life in older adults with sarcopenia. It may not adequately address individual needs, limiting their effectiveness.

Objective: This study aimed to evaluate the effects of a Mixed Reality–based Physical Therapy platform (Mr.PT) compared with Conventional Physical Activity (CPA) programs on quadriceps muscle thickness, balance confidence, independence in ADLs, and quality of life in older adults with sarcopenia.

Methods: In this preliminary randomized controlled trial, 30 older adults with sarcopenia were randomly assigned to either the Mr.PT group or the CPA group. Both groups participated in 30-minute sessions, five times per week, for four weeks. Primary outcomes included quadriceps muscle thickness. Secondary outcomes included the Activities-specific Balance Confidence (ABC) Scale, Katz Index of Independence in Activities of Daily Living (KIADL), and the 12-Item Short-Form Survey (SF-12). Outcomes were assessed at baseline and after the intervention. Analysis of variance (ANOVA) was used to assess time and group differences.

Results: ANOVA demonstrated significant time effects on muscle thickness, ABC scores, KIADL scores, and SF-12 scores ($p < 0.05$). Post hoc analyses revealed that participants in the Mr.PT group achieved greater improvements in quadriceps muscle thickness and quality of life among older adults with sarcopenia. Further large-scale trials are warranted to confirm these findings and to optimize intervention protocols.

Conclusions: This preliminary study suggests that a Mixed Reality–based physical therapy platform may offer enhanced benefits for improving muscle thickness and quality of life among older adults with sarcopenia. Further large-scale trials are warranted to confirm these findings and to optimize intervention protocols. Clinical Trial: KCT0010241

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Abstract

Background: Older adults with sarcopenia often engage in therapeutic exercises to improve muscle thickness, balance confidence, activities of daily living (ADL), and quality of life (QOL). However, conventional face-to-face group exercise programs are typically standardized and may not adequately address individual needs, limiting their effectiveness.

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Results: ANOVA demonstrated significant time effects on muscle thickness, ABC scores, KIADL scores, and SF-12 scores ($p < 0.05$). Post hoc analyses revealed that participants in the Mr.PT group

achieved greater improvements in quadriceps muscle thickness and SF-12 scores compared to the CPA group.

Conclusion: This preliminary study suggests that a Mixed Reality-based physical therapy platform may offer enhanced benefits for improving muscle thickness and quality of life among older adults with sarcopenia. Further large-scale trials are warranted to confirm these findings and to optimize intervention protocols.

Trial Registration: KCT0010241

Keywords: Sarcopenia, Mixed reality, Muscle thickness, Risk of fall

1. Introduction

Mixed Reality (MR)-based digital therapeutics have emerged as novel and promising technologies for addressing the growing healthcare demands of aging populations¹. Sarcopenia, defined as the progressive loss of skeletal muscle mass and strength with advancing age, represents a significant geriatric concern associated with frailty, increased fall risk, impaired activities of daily living (ADL), and diminished quality of life (QOL)^{2,3}. This geriatric issue is widespread and progressive, and can lead to hospitalization⁴⁻⁶.

Traditional interventions for sarcopenia, such as group-based or resistance exercise programs, offer clinical benefits but are limited by their standardized design, often requiring fixed schedules, group coordination, and in-person delivery^{3,7}. These limitations were exacerbated during the COVID-19 pandemic, highlighting the urgent need for flexible, individualized therapeutic strategies^{8,9}. Moreover, conventional group exercise typically lacks sufficient personalization, making it difficult to optimally engage and progress participants based on their functional capabilities.

To address these gaps, we developed a Mixed Reality-based Physical Therapy (Mr.PT) platform designed to deliver personalized, engaging, and accessible exercise interventions. Mr.PT employs commercially available MR devices that integrate virtual and real-world elements, enabling users to interact with digital environments while maintaining physical context¹⁰. Mr. PT comprises inexpensive, motivational, fun, and intensive devices¹¹. The Mr. PT platform is designed to work with MetaQuest, and the software allows clinicians and clients free access to the platform without spatiotemporal constraints. The movement kinematics when reaching, grasping, transporting, and releasing objects in a virtual environment are comparable to those in the physical world^{12,13}. Unlike Virtual Reality (VR), which fully immerses users in synthetic environments, MR systems allow simultaneous interaction with both real and virtual objects, thereby supporting more realistic and functionally relevant training experiences¹⁴. Proprioceptive feedback has been suggested to exploit the multimodal aspects of correct active movements. However, clinical research on these systems has

mainly focused on neurorehabilitation training rather than geriatric physical therapy.

While MR-based interventions have been explored extensively in the fields of neurorehabilitation and motor recovery, evidence supporting their use in geriatric physical therapy—particularly for sarcopenia management—is scarce. Thus, this study aimed to evaluate and compare the effects of Mr.PT and Conventional Physical Activity (CPA) programs on quadriceps muscle thickness, balance confidence, ADL independence, and QOL among older adults with sarcopenia.

Given the accelerating trends of global aging, especially in countries like South Korea and Japan, there is an urgent need to develop accessible, scalable, and individualized rehabilitation interventions. MR-based platforms such as Mr.PT may offer sustainable solutions to enhance functional outcomes and support independent living among older adults.

2. Methods

2.1. Participants

A convenience sample of 30 older adults with sarcopenia (mean age: 75.3 ± 9.9 years; all female) was recruited from a geriatric welfare center. Inclusion criteria were: (1) age ≥ 65 years, (2) diagnosis of sarcopenia by a medical doctor based on established clinical criteria, (3) absence of chronic obstructive pulmonary disease, cancer, kidney disease, hypertension, hyperlipidemia, stroke, diabetes mellitus, obesity, osteoporosis, or fractures, and (4) body mass index (BMI) < 23 kg/m².

The study protocol was approved by the Institutional Review Board of Jeonju University (IRB No. jjIRB-250206-HR-2024-1203) and was registered with the Korean Clinical Trials Registry (KCT0010241). All participants provided written informed consent before participation.

2.2. Randomization and Blinding

Participants were randomized into either the Mr.PT group or the CPA group using a simple coin-flip method. Randomization occurred prior to baseline assessments to minimize bias. Assessments were conducted by blinded evaluators who were unaware of group assignments, ensuring a single-

blinded study design.

2.3. *Experimental setup*

A procedural checklist was used to standardize all experimental procedures. Equipment was calibrated daily before data collection. Baseline assessments included quadriceps muscle thickness, the activities-specific balance confidence (ABC) scale, the Katz index of independence in activities of daily living (KIADL), and the short form -12 (SF-12) survey. Both groups were supervised by licensed physical therapists during exercise sessions. For the Mr.PT group, a computer technician was present during interventions to address potential technical issues but did not interact with participants or influence the sessions.

2.4. *Ultrasound imaging measurement of quadriceps muscle thickness*

An ultrasound probe (Bionet, Seoul, Republic of Korea) was used to obtain images of the rectus femoris muscle. All 2-D ultrasound imaging acquisitions were acquired using a ultrasonographic system equipped with a single sweep volumetric transducer. The apparatus had a linear vascular probe with a bandwidth of 3.3–8.0 MHz, an aperture of 2.9 cm, and a maximum scanning depth of 8 cm, in addition to a phased array cardiac probe with a bandwidth of 1.7–3.8 MHz and a field of view of 70°¹⁵. All participants were scanned while lying comfortably in the supine position. According to a previous study, the examiner positioned the probe on the anterior aspect of the quadriceps, perpendicular to its long axis, halfway between the proximal end of the patella and the anterior superior iliac spine. The examiner identified the rectus femoris, vastus intermedius, femur, and subcutaneous adipose tissues. To reduce artifacts, the skin was treated with excess gel. To examine the inter- and intra-rater reliability of the bilateral limbs, three examiners acquired pictures¹⁵. Among the three examiners were three physical therapists. The examiners were experts who had used ultrasound for evaluation in a clinical context for a minimum of three years. To prevent variations in the measurement and analysis of muscle data, each trial performed by the three examiners was performed separately within two hours of the initial assessment¹⁵. The top border of the rectus

femoris was marked with a pointer on the screen of the ultrasound device. This enabled the device to determine muscle thickness as the total rectus femoris muscle thickness. Three measurements were made by each examiner to determine intra-rater reliability^{15,16}. The participants returned to their starting position after every investigation, and any gel or markings were removed from their skin by cleaning it. This minimized the possibility of measurement bias, such as anchoring, and guaranteed independent acquisition of each image and dataset (Fig 1).

2.4.1. Activities-specific balance confidence (ABC) scale

An indirect indicator of falling risk, the ABC scale, was used to gauge the participants' confidence in their ability to perform a range of ambulatory tasks without feeling unsteady or falling. The 16 ABC scale components have scores ranging from 0 (no confidence) to 100 (full confidence)¹⁷. The validity and reliability of the measurement tests have been thoroughly proven elsewhere¹⁷.

2.4.2. Katz index of independence in activities of daily living

The best tool for determining a client's functional status is a measure of their capacity to perform everyday tasks independently¹⁸. Age-related changes and health problems frequently result in a decline in the functional status of older adults. This decline often places older adults in a downwards health spiral. An effective way to evaluate the health status of older adults is through their functional abilities¹⁸. An objective assessment that provides objective data helps indicate a decline or improvement in health status, allowing physical therapists to plan and intervene appropriately. The validity and reliability of the measurement tests have been thoroughly proven^{18,19}.

2.4.3. Geriatric quality of life

Twelve items comprise the SF-12, which is a health-related quality of life survey. Using this information, we evaluated eight health areas including mental and physical health²⁰. General health, bodily discomfort, physical roles, and physical functioning were domains associated with physical health. Vitality, social functioning, emotional roles, and mental health are among the scales pertaining to mental health. The validity and reliability of outcome measurement tests have already been demonstrated in other contexts²¹.

2.5. *Intervention*

Both Mr. PT and TPT were assigned to participants in a randomized controlled trial, with a frequency of 30 min, and administered five times per week for four weeks. All participants were assessed using two (pre and post) evaluations.

Mr.PT group:

Participants in the Mr.PT group engaged in a Mixed Reality-based exercise program utilizing the MetaQuest head-mounted display system (Funrehab, Daejeon, Republic of Korea). The intervention was designed to simulate a variety of functional and cognitive tasks within an interactive virtual environment that seamlessly integrated with real-world movement^{12,22}. Each session began with participants standing or seated in a safe area, where they wore the MR device and received brief instructions on the day's activities. Initial exercises involved evading virtual objects approaching from various directions, requiring participants to shift their weight, adjust their posture, and take small steps to avoid collisions. This activity was intended to enhance dynamic balance, postural control, and lower limb reaction times¹⁰.

Subsequent tasks incorporated upper extremity movements, where participants were asked to "shoot" at virtual targets appearing at random locations within their field of vision by performing rapid and precise shoulder abduction or flexion movements. This shooting task aimed to improve upper body coordination, reaction speed, spatial awareness, and proprioception²³. As participants progressed through the program, combined tasks were introduced, simultaneously requiring both footwork (for dodging) and shoulder movements (for targeting) to complete challenges²⁴. These integrated activities were specifically designed to train motor planning, divided attention, and cognitive-motor multitasking, which are often impaired in older adults with sarcopenia. The difficulty level of the virtual tasks was automatically adjusted based on participant performance, ensuring an appropriate balance between challenge and skill to maintain motivation and maximize engagement (Fig 2)²⁵. Verbal encouragement and visual feedback were provided throughout the

sessions by the MR system, further supporting adherence and participant satisfaction. Each MR-based exercise session lasted 30 minutes and was conducted five times per week over the four-week intervention period, under the supervision of a trained physical therapist and a computer technician who managed technical setup but did not influence participant behavior (Fig 3).

CPA group:

Participants assigned to the CPA group performed a conventional, therapist-led exercise program focused on maintaining and improving musculoskeletal strength, balance, and mobility. Sessions took place in a standard exercise room equipped with balance mats, chairs, and minimal resistance equipment²⁶. Each CPA session consisted of warm-up activities such as marching in place and dynamic stretching, followed by structured moderate-intensity gait training across flat surfaces. Gait exercises incorporated variations in speed and direction to promote adaptability and coordination. Strength training exercises emphasized the major muscle groups responsible for functional mobility. Participants performed sets of hip flexion, extension, and abduction exercises, as well as knee flexion and extension drills, often using bodyweight resistance or elastic bands to adjust intensity²³. Balance training involved static and dynamic activities, including one-legged standing with eyes open, tandem standing, and tandem walking along a straight line. Each exercise was modified according to individual ability, with progression achieved by increasing task complexity or duration. Upper extremity exercises targeted shoulder abduction, extension, and flexion using light dumbbells or resistance bands, aiming to maintain upper limb functional strength necessary for daily tasks. Each CPA session was also 30 minutes in duration and was delivered five times per week for four weeks. Exercises were supervised by licensed physical therapists who monitored participant performance, provided feedback, and ensured safety throughout the program^{14,27}. To match intervention dose and ensure comparability, the frequency, session length, and basic training volume were standardized between the Mr.PT and CPA groups.

2.6. Statistical analysis

Descriptive statistics (means $\pm$ standard deviations) were calculated for all continuous variables. The Kolmogorov-Smirnov test confirmed normality assumptions. Repeated-measures analysis of variance (ANOVA) was used to compare pre- and post-intervention changes within and between groups. Tukey's post-hoc tests were applied to examine significant interactions. The chi-square test was used for categorical data (e.g., sex). Power analysis using G*Power 3.1.9.7 indicated that a sample size of 27 participants would achieve 80% power with an effect size of 0.5 ($\alpha=0.05$); thus, 30 participants were recruited to allow for potential dropout. Observed power was calculated post hoc for key outcomes. A significance threshold of $p < 0.05$ was used for all analyses. Statistical analyses were conducted using SPSS version 26.0 (IBM Corp., Armonk, NY, USA), IL, USA) was used for the statistical analyses. A 0.05 p-value was determined.

3. Results

3.1. *Demographic data*

Table 1 shows the demographic characteristics of the participants. Each participant completed all experimental tasks and exercises. The TPT and Mr.PT groups did not differ significantly in terms of sex, age, height, weight, or BMI ($p > 0.05$).

3.2. *Quadriceps muscle thickness and KIADL measurements*

Repeated-measures ANOVA revealed a significant time effect ($p=0.001$) for quadriceps muscle thickness and KIADL, indicating improved muscle thickness and activities of daily living for participants. No significant difference in KIADL scores was observed between the groups ($p=0.09$). The interaction post hoc test revealed a greater improvement in quadriceps muscle thickness in Mr. PT than in TPT, suggesting that quadriceps muscle thickness is related to sarcopenia after Mr. PT than in TPT (Table 2).

3.3. *ABC scale and SF-12 measurements*

Repeated-measures ANOVA revealed a significant time effect ($p=0.001$) for the ABC scale

and SF-12, indicating improved fall confidence and quality of life for participants. No significant difference in the ABC scale scores was observed between the groups ($p=0.23$). The interaction post-hoc test revealed a greater improvement in SF-12 in Mr. PT compared to TPT, suggesting that quality of life is related to sarcopenia after Mr. PT compared to CPA (Table 3).

4. Discussion

This preliminary study aimed to assess the feasibility and potential benefits of a Mr.PT platform compared to CPA in older adults with sarcopenia. Both interventions were associated with improvements in quadriceps muscle thickness, balance confidence, ADL, and QOL. Baseline characteristics were similar between groups, minimizing confounding effects and supporting the validity of group comparisons. The observed improvements in quadriceps muscle thickness suggest that both interventions successfully stimulated muscle adaptation, although the Mr.PT program appeared to elicit a greater hypertrophic response.

The quadriceps muscle thickness related sarcopenia analysis demonstrated that the improvement in muscle thickness (9.1%) was significantly different between the groups. This finding is consistent with those of the previous studies. Chen et al. (2021) reported increased muscle strength (10.2%) using virtual reality compared with the control group in 30 participants with sarcopenia²⁸. Jeon and Kim (2020) reported increased muscle parameters (8.8%) using an augmented reality-based exercise program compared with the control group in 30 participants with sarcopenia²⁹.

VR training has shown promising results in improving physical function and muscle strength in older adults. An 8-week unsupervised virtual reality exercise program significantly enhanced hip muscle strength and balance control in older adults compared to a control group³⁰. Similarly, a VR fitness program improved muscular fitness and body composition in young untrained men, although some measures showed less improvement than traditional exercise^{13,31}. VR training also increased lower extremity muscle activation in older subjects after an 8-week intervention using a Wii Fit²³. Previous studies have highlighted the potential of MR technologies to enhance engagement,

cognitive-motor integration, and exercise adherence in various populations. Muraki et al. (2013) demonstrated that muscle thickness assessed by ultrasound can effectively estimate knee extension muscle strength in females³². Our findings align with this growing body of evidence and suggest that MR-based exercise interventions may offer meaningful advantages for older adults at risk of sarcopenia.

The activities daily of living analysis demonstrated that the improvement in KIADL (7.7% and 7.9%, respectively) was significantly different pre- and post-intervention in both groups. This finding is consistent with those of the previous studies. Liao et al. (2019) found increased ADL function (7.73%) using virtual reality compared to the control group in 34 older adults with mild cognitive impairment³³. Arlati et al. (2019) reported increased ADL (10.23%) using virtual reality-based applications compared to the control group in older people³⁴. Gamito et al. (2020) found improved executive function using a virtual reality-based program (22.5%) compared to the control group in 50 community-dwelling older individuals²⁶. Gamification platforms increase user loyalty by providing highly immersive, engaging, and entertaining virtual environments for various locations and challenges. Consistent with previous analyses, our findings imply that the application of commercial virtual reality systems, including the Xbox Kinect, PlayStation, and Nintendo Wii, may be advantageous and practical for enhancing functional daily living in the geriatrics^{35,36}.

We found that MR was more effective and provided more significant evidence in the field of occupation and ambulation in ADL performance^{22,24,25}. VR has emerged as a promising tool for cognitive rehabilitation and training in activities of daily living for patients with neurological disorders. Studies have shown that Virtual-based interventions can improve cognitive functioning, attention, memory, and executive function in stroke patients^{5,13}. VR systems allow for personalized progressive training in ADL tasks by providing real-time feedback to patients. These systems offer immersive and realistic environments that simulate everyday activities, making rehabilitation more engaging and motivating for users³⁷. Research has also demonstrated the feasibility and usability of

virtual reality-based ADL training, with handheld controllers proving to be more intuitive and less demanding than traditional mouse inputs ³⁸. Overall, virtual technology has great potential for enhancing cognitive rehabilitation by offering ecologically valid and personalized training experiences that can effectively supplement conventional therapeutic methods.

The fall confidence analysis demonstrated that the improvement in the ABC scale (12.15% and 10.97%) was significantly different pre- and post-intervention in both groups. This finding is consistent with those of the previous studies. Using Xbox gaming, Zahedian-Nasab et al. (2021) found that decreasing risk of falling (7.91%) using Xbox gaming than control group in 60 older individuals ³⁹. People find virtual games emotionally and physically taxing, and when playing, the players' motions constantly change direction, pace, and speed. Therefore, rapid brain processing, adjustments, and control of body balance are required ^{25,38}. In addition, older adults can effectively employ safe and reasonably priced technologies in their homes ⁴⁰. Virtual reality technology is promising for fall prevention and improvement in confidence in older adults. Virtual reality balance exercise programs can reduce the risk of falling and fear of falling in community-dwelling women ⁴¹. A study using a balance rehabilitation unit found significant improvements in balance parameters, reduced falls, and lower fear of falling in older adults with a history of falls ⁴². However, the effectiveness of VR interventions depends on user acceptance. Research on VR headsets for fall prevention has found that the intention to use was positively predicted by perceived usefulness, enjoyment, and ease of use ⁴³.

Quality of life analysis demonstrated that the improvement in SF-12 (4.68%) was significantly different between the groups. This finding is consistent with those of the previous studies. Barsasella et al. reported an improved quality of life (15.9%) using virtual reality compared to a control group in 60 older adults ⁴⁰. Wang et al. (2024) found an increased quality of life (0.37%) using a semi-immersive virtual reality intervention compared with the control group in 100 older adults ⁴⁴. VR-based interventions have shown promising results in improving older adults' quality of

life. Studies have demonstrated that virtual reality can enhance the physical, cognitive, psychological, and social well-being of this population⁴⁴. MR-based exercises have been found to significantly improve overall quality of life, mental and physical health, social relationships, and depression symptoms in older adults^{13,22}. While virtual, augmented, and mixed reality applications have become more developed in the physical and cognitive domains, research in the areas of psychological and social well-being is still emerging⁴⁵. These findings suggest that digital therapeutic technology has a significant potential to enhance various aspects of older adults' quality of life.

This study has several limitations that should be addressed in future research. First, although we assessed important clinical outcomes such as quadriceps muscle thickness, activities of daily living, balance confidence, and quality of life, we did not evaluate the neurophysiological mechanisms underlying functional improvements, such as cortical and subcortical changes. Second, quantitative measures of exercise performance were not available, limiting the precision of exercise intensity monitoring. Third, the follow-up period was relatively short, and sustainability of the intervention effects over the long term remains unknown. Future large-scale studies incorporating neurophysiological assessments, objective exercise monitoring tools, and longer follow-up periods are warranted to validate and extend our findings.

5. Conclusion

Clinical research has indicated that mixed-reality platform facilitated therapeutic exercise is beneficial for improving muscle thickness, ADL, fall confidence, and quality of life in older adults with sarcopenia. Our results provide therapeutic evidence that Mr. PT improves the recovery of quadriceps muscle thickness and quality of life in patients with depression and anxiety. Most importantly, the Mr. PT platform allows autonomous provision of real-time audiovisual feedback and effective training, which could serve as a basis for advanced rehabilitation sciences and medical evidence.

Data Sharing Statement

Data used and/or analyzed for the current study are available from the corresponding author upon reasonable request

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Figure legend

Fig 1. Rectus femoris ultrasound imaging

Fig 2. Mixed reality platform-based physical exercise therapy

Fig 3. Mixed reality platform

Figure 1. Rectus femoris ultrasound imaging

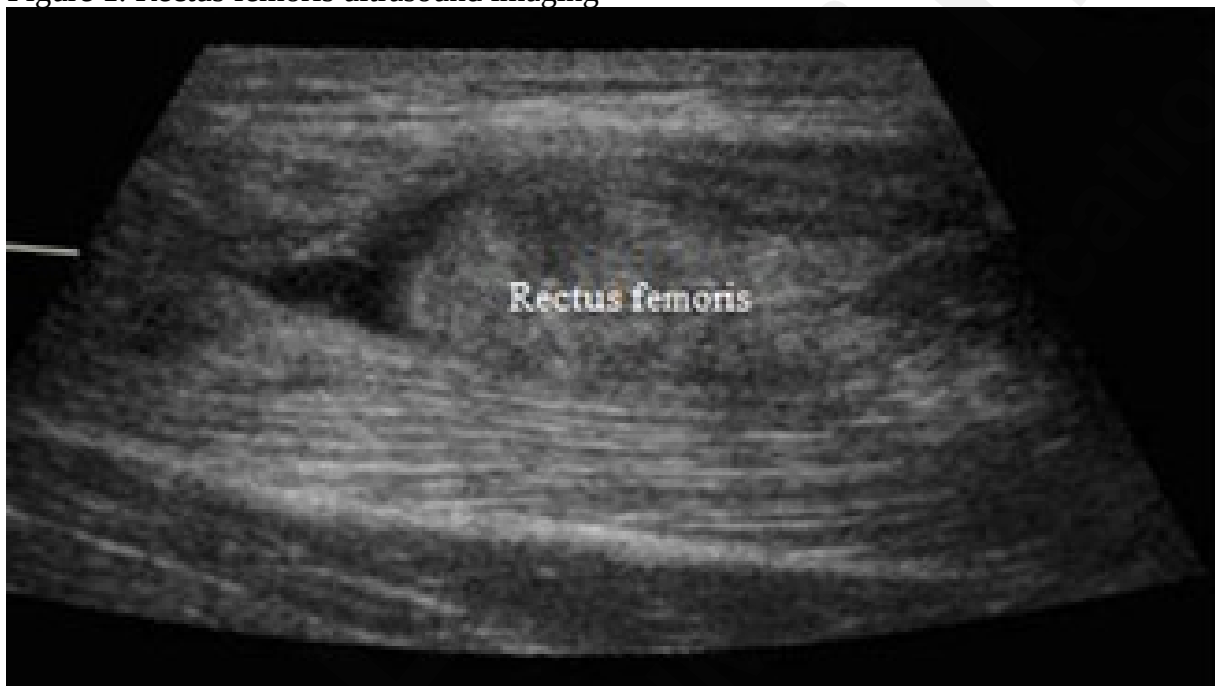


Figure 2. Mixed reality platform-based physical exercise therapy

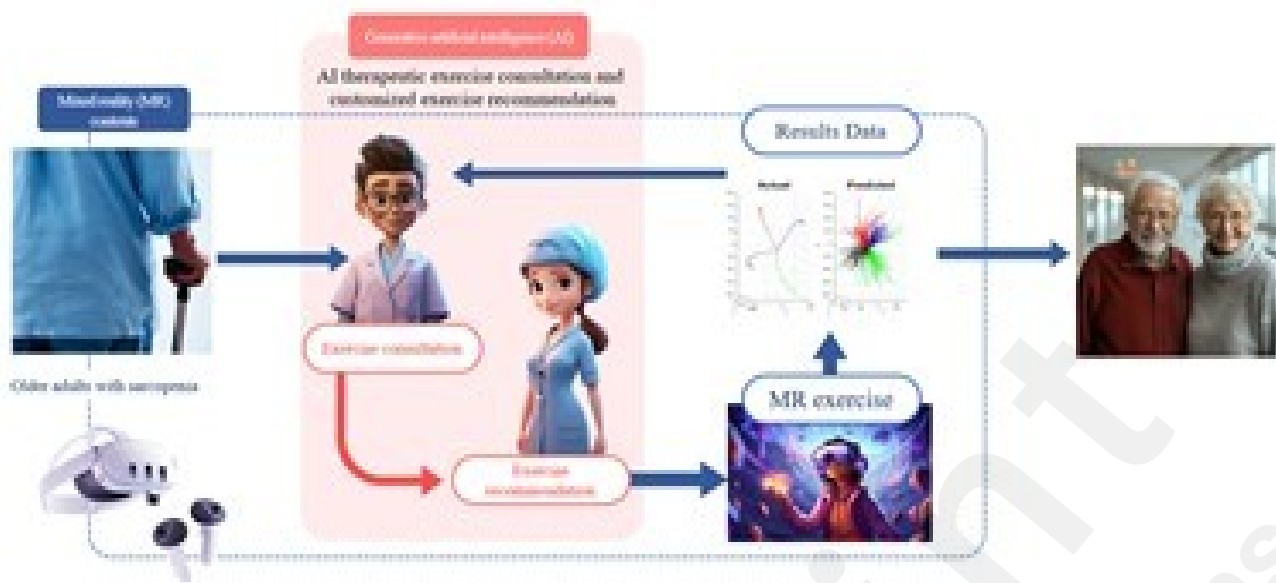


Figure 3. Mixed reality platform

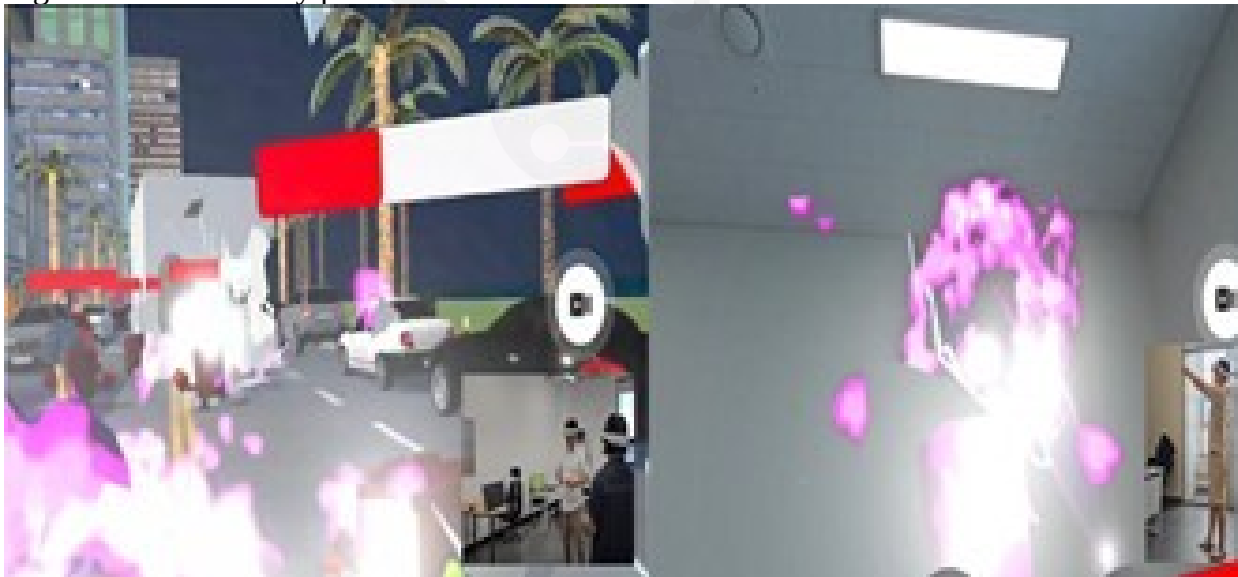


Table 1. Participants' demographic characteristics (N=30)

Characteristics	Mr.PT ^a (n=15)	TPT ^b (n=15)	P-value
Age (years)	76.24±8.7	74.88±9.1	0.68
Sex (Male/Female)	0/15	0/15	1.00
Height (cm)	153.12±10.11	155.88±8.21	0.31
Weight (kg)	54.13±6.13	56.27±4.88	0.45
BMI (kg/m ²)	20.11±1.81	20.83±0.91	0.23

^aMr. PT, mixed reality platform-based physical exercise therapy; ^bTPT, Traditional physical therapy; BMI, Body mass index.

Table 2. Quadriceps muscle thickness and KIADL measurement

	Mr.PT ^a		TPT ^b		P-value		
	Pre-	Post-test	Pre-test	Post-test	Time	Between	Time ×

	test				effect	groups	group
Quadriceps muscle thickness (mm)	15.83±1.83	17.13±1.77	15.71±2.01	16.22±1.38	0.001*	0.02*	0.001*
KIADL ^c	3.90±0.32	4.20±0.43	3.80±0.37	4.10±0.41	0.001*	0.09	0.08

^aMr. PT, mixed reality platform-based physical exercise therapy; ^bTPT, Traditional physical therapy; ^cKIADL, Katz Index of Independence in Activities of Daily Living; * $P < 0.05$

Table 3. ABC scale and SF-12

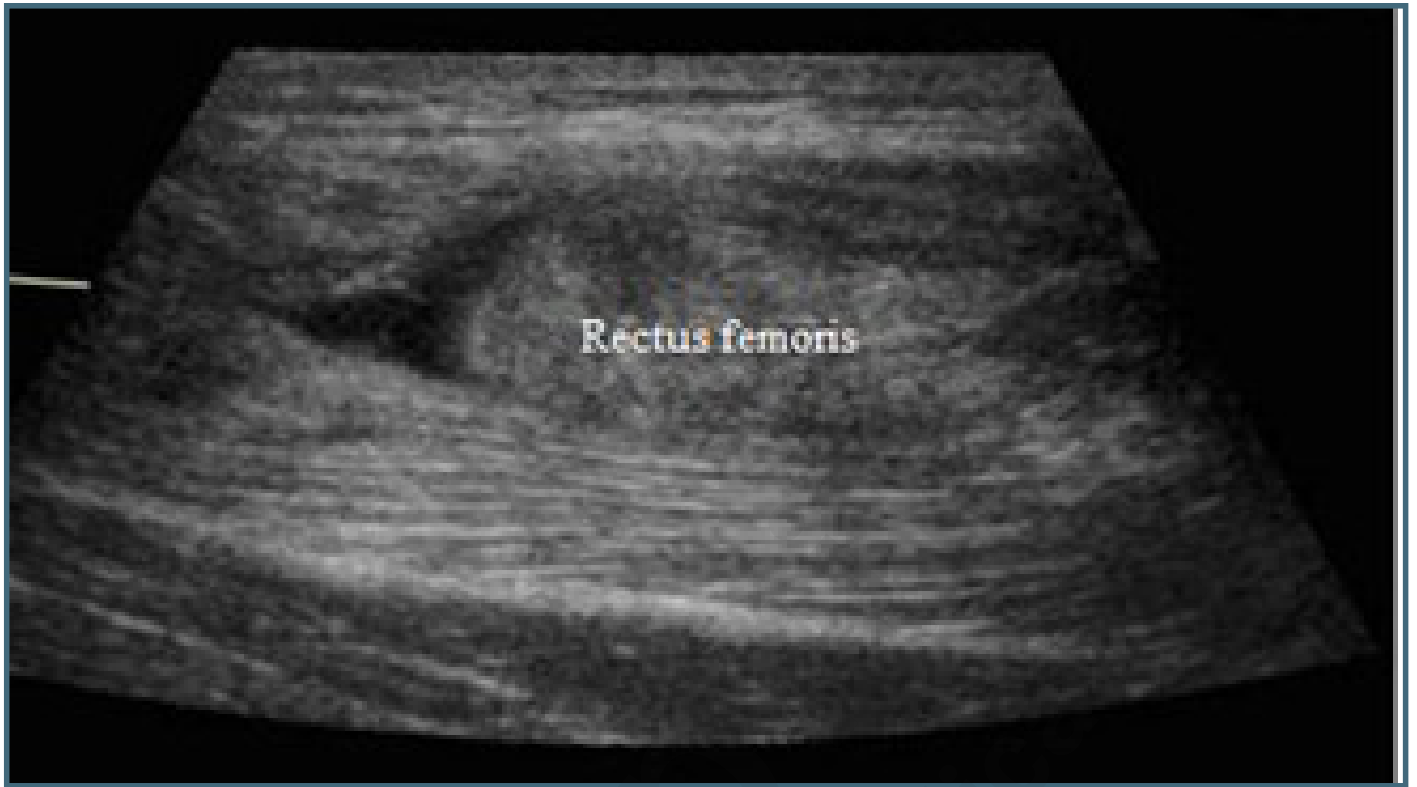
	Mr.PT ^a		TPT ^b		P-value		
	Pre-test	Post-test	Pre-test	Post-test	Time effect	Between groups	Time × group
ABC scale ^c	1223.48±253.12	1372.18±178.55	1218.68±188.12	1349.88±163.88	0.001*	0.23	0.41
SF-12 ^d	60.84±4.88	74.20±7.88	63.18±3.78	74.10±8.31	0.001*	0.02*	0.04*

^aMr. PT, mixed reality platform-based physical exercise therapy; ^bTPT, Traditional physical therapy; ^cABC scale, activities-specific balance confidence scale; ^dSF-12, Short form-12; * $P < 0.05$

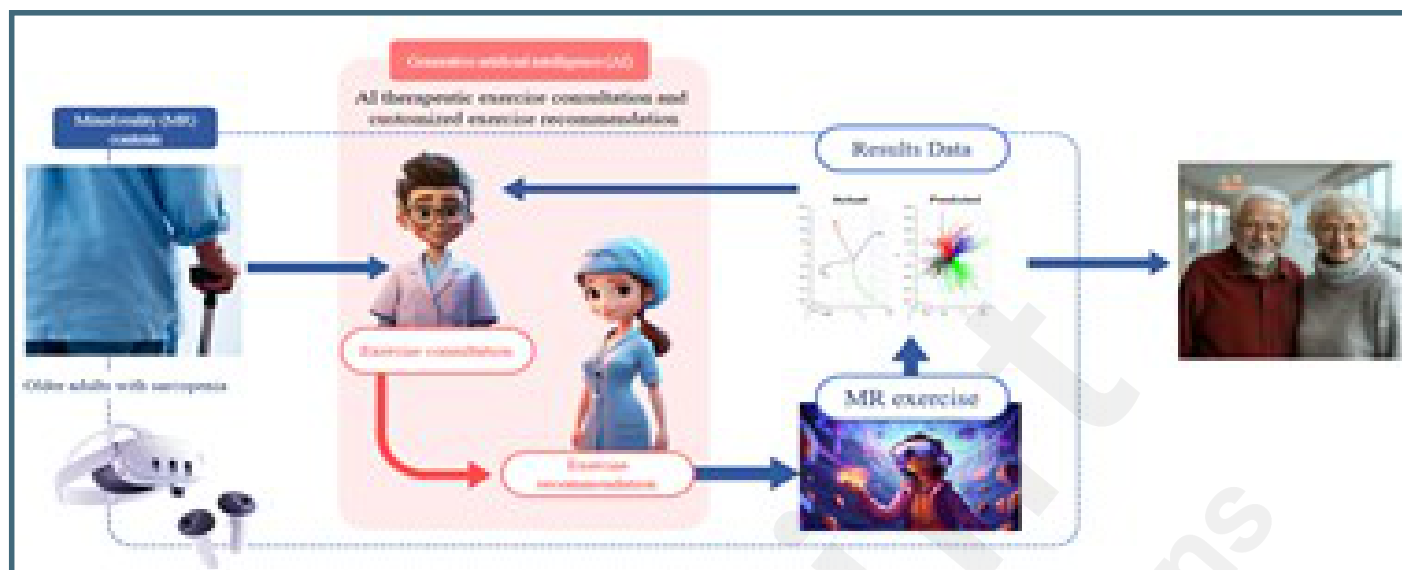
Supplementary Files

Figures

Rectus femoris ultrasound imaging.



Mixed reality platform-based physical exercise therapy.



Mixed reality platform.

