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The effects of 6-week home-based static stretching, dynamic stretching, or eccentric exercise interventions on muscle-tendon properties and functional performance in older women

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ABSTRACT

Background: Joint inflexibility is acknowledged as a significant contributor to functional limitations in the older adult, with lengthening-type exercises identified as a potential remedial approach. Nevertheless, the responses to eccentric exercise in female older adults have not been extensively studied especially in home-based environment. Here, we aimed to assess the effectiveness of home-based static stretching (ST), dynamic closed-chain stretching (DCS), or eccentric exercise (ECC) interventions on flexibility, musculotendinous architecture, and functional ability in healthy older women.

Methods: We randomly assigned 51 healthy older women (age 65.9 ± 3.4 years) to one of three interventional exercise groups: DCS ($N = 17$), ECC ($N = 17$), or ST ($N = 17$). The training was performed 3 times a week for 6 weeks. The participants' musculotendinous stiffness, fascicle length, eccentric strength, and functional capacities were measured before the intervention, after 6 weeks of exercise, and at a 1-month follow-up.

Results: The results showed that all three interventions improved hamstring flexibility and passive ankle dorsiflexion ($p < 0.001$), with increased biceps femoris and medial gastrocnemius fascicle length ($p < 0.01$). However, there was no significant change in musculotendinous stiffness. The ECC intervention produced a greater improvement in knee flexor and calf eccentric peak torque ($p < 0.05$), and gait speed ($p = 0.024$) than the other two interventions. The changes in flexibility and knee flexor strength remained for up to 4 weeks after detraining.

Conclusion: In conclusion, the present study suggests that home-based ECC may be more beneficial in enhancing physical capacities in older women compared with either DCS or SS interventions.

1. Introduction

The aging process is associated with decreased flexibility, which has been linked to various factors, such as collagen cross-linking, changes in intramuscular adipose tissue and extracellular water content, and reduced collagen fibril diameter.[1–3] These changes can lead to functional limitations and reduced quality of life for older adults. There is a general agreement that static stretching exercise is an effective tool for improving flexibility in both younger and older adults.[4–6] Dynamic stretching exercise may be a more suitable for older adults, as it offers the potential to simultaneously both improve flexibility and maintain muscle strength/power as seen in young participants.[7–9] However, caution must be applied to ensure the safety of dynamic stretching exercises, particularly in older adults, as difficulties with movement coordination or high exercise velocity can increase the risk of injury. Besides strength benefits, which are important contributors to physical functional performance in older people,[10,11] eccentric strength training can also improve joint ROM, which can be explained by sarcomerogenesis and changes in the stretch reflex.[12,13] Recent findings highlight the importance of eccentric strength training, as it can be equally effective or even more advantageous than concentric training in enhancing leg strength, mobility, and postural stability in older

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adults.[14,15] However, there are insufficient data available on the impact of eccentric exercise on flexibility in older adults.

Of interest is the use of home-based exercise, which is a feasible method for enhancing health status, reducing expense, and is highly suitable during extreme situations, such as the current COVID-19 pandemic crisis. Previous research has demonstrated the safety and efficacy of high-intensity training in older adults.[16,17] However, the impact of home-based flexibility or eccentric exercise on muscle morphology, mechanical characteristics, and functional performance in older adults remains unclear. It is worth mentioning that a relatively novel muscle quality indicator, such as changes in echo intensity (EI) detected by ultrasound (US) imaging [18], may be linked to the response to elderly training, but there is still a lack of data. Moreover, it is also unclear whether prescribing eccentric exercise is effective for older women, as they tend to be less viable in strength exercises than men,[19] and sex should be considered when observing the sensation or viscoelastic property changes in response to stretching exercise.[20] Furthermore, while there may be benefits associated with the three home-based interventions for functional performance, it is unclear how long these effects may last.

The present study aimed to evaluate and compare the effects of 6 weeks of home-based dynamic or static stretching or eccentric exercise on various musculoskeletal and functional parameters in older women, with a follow-up assessment 1 month after the intervention. Specifically, we investigated changes in musculotendinous architecture, flexibility, passive stiffness, leg strength, and functional performance. Our hypothesis was that eccentric exercise and dynamic stretching would result in less improvement in ROM compared with static stretching intervention, but would promote increases in musculotendinous unit stiffness, which are known to improve functional capacity in older adults. Elaborating on most beneficial exercise program and mechanisms related with exercising outcomes will provide useful information for more precise recommendations for senior fitness training.

2. Materials and methods

2.1. Participants

We included 51 healthy older women in this study [aged 65.9 ± 3.4 years with a body mass index (BMI) of 22.1 ± 2.4 kg m^{-2}]. The sample size was based on changes in fascicle length (FL) in previous study.[7] An error type of 0.05, a statistical power of 0.80, and a minimal sample size of 13 were defined by G power software, which was subsequently increased by 30% (N = 17) in each group to account for expected dropout events. Participants were recruited from Saen Suk and surrounding communities in Chonburi Province, Thailand, through social media advertising. The study included individuals aged 60–75 years who were eligible to participate after undergoing pre-screening using the Physical Activity Readiness Questionnaire (PAR-Q) and demonstrated independent walking ability. Exclusion criteria included any neuromuscular or skeletal injury associated with the lower extremities or lower back in the previous 6 months, any regular stretching or strengthening training regimen, inability to follow the instructions given during the assessment, moderate to severe back or lower extremity pain (visual analog scale >3/10), or obesity (BMI >24.9 kg m^{-2}). After the testing and training procedures had been carefully acknowledged, the participants provided written informed consent to participate in the study, which had been approved by the Research and Innovation Administration Division of Burapha University Ethics Committee (IRB1-007/2565) following the contemporary (2013) revision of the Declaration of Helsinki.

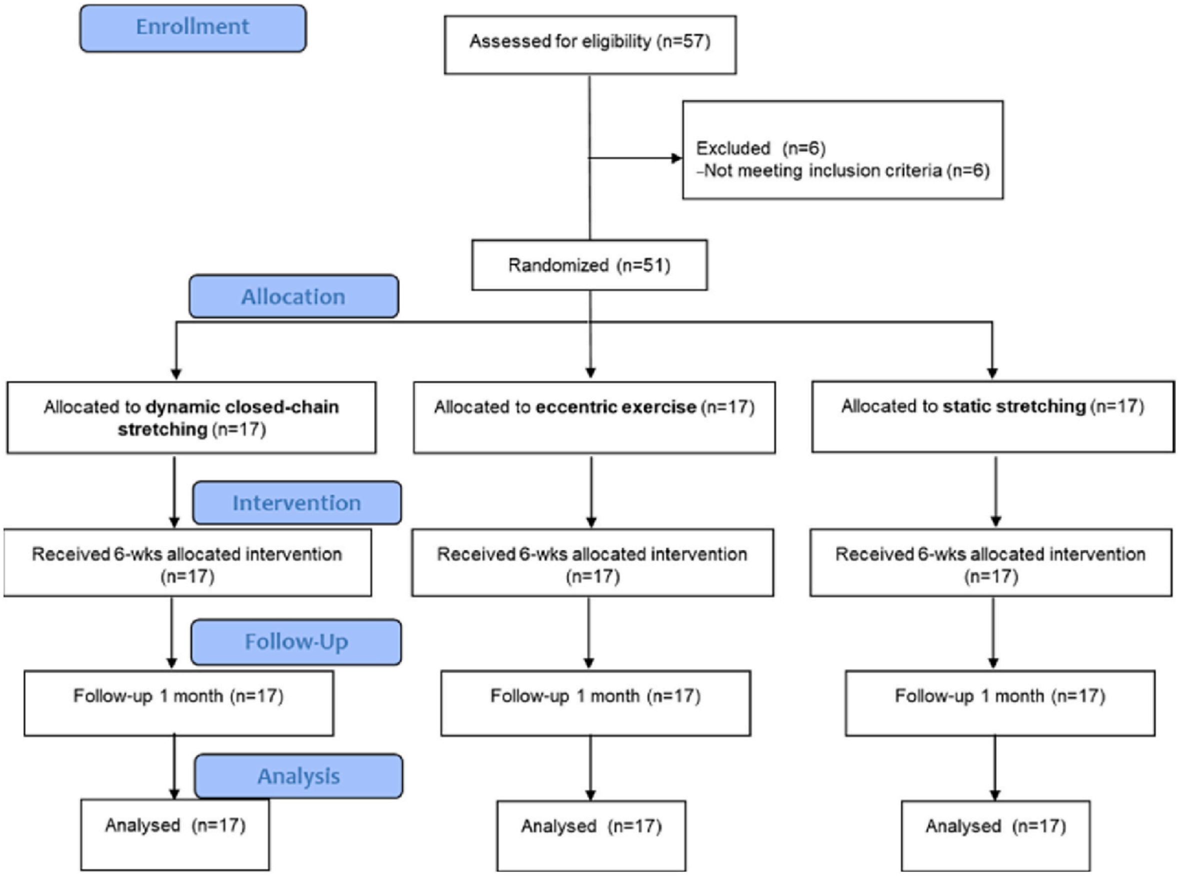

Fig. 1. The study flowchart.

2.2. Study design

The study design was a randomized, double-blinded clinical trial, adhering to the guidelines outlined in the CONSORT 2010 flow diagram. (Fig. 1). The study protocol was registered on the Thai Clinical Trials Registry (TCTR) identification number of TCTR20230321013. A few days before the interventions, all participants undertook a familiarization session at the Physical Therapy Department, Allied Health Science Faculty, Burapha University. They were randomly assigned to three interventional exercise groups [dynamic closed-chain stretching (DCS), eccentric exercise (ECC), and static stretching (ST)] by blocks of six randomizations using sealed, numbered, and opaque envelopes. The procedure of categorizing participants into groups was based on age similarity, serving as the principal confounding criterion in this study. The musculotendinous ultrasound imaging and stiffness, flexibility, and eccentric strength variables served as primary outcomes, with functional performance considered as a secondary outcome. All measurements were made by the same investigators in the same order at pretraining, two days after 6 weeks of training, and at 1 month detraining follow-up. The selected timing of assessments was based on the standard 6–12-week cycles typically associated with flexibility and strength training, while de-adaptation can be apparent after as short as 4 weeks. The primary investigators did not know which program the participant was assigned to, and the participant was unaware of the details of the other intervention programs.

2.3. Measurements

At the beginning of the testing day, participants warmed up with 7 min of exercise on a cycle ergometer just after the ultrasound imaging measurement. Both participant's legs were trained, but only right leg parameters was measured.

2.3.1. Musculotendinous ultrasound imaging

B-mode ultrasonography (M5 series, Shenzhen, Mindray Bio-Medical, China) was used to capture leg images with a linear 4 cm, 7.5 MHz probe (MSK preset) consistently across participants using settings of 10 MHz, 54 dB gain, and a dynamic range of 60 at a depth of 5 cm. With the participant lying prone on a bed, the probe was located 15 cm above the popliteal line for the long head of biceps frmoris (BF) muscle images. In the same position, with the examined foot relaxed in a neutral position (90°), images of medial gastrocnemius (MG) muscle were obtained 10 cm below the popliteal line. During resting and at the end point during the passive straight leg raise (SLR) and dorsiflexion (DF) procedures, two images of each muscle were captured as images in the transverse and longitudinal propagations with some gel and minimal pressure on the probe.

Muscle thickness (MT) and pennation angle (PA) were all analyzed offline with Tracker version 6.0.10 software for the longitudinal images, in which MT indicates the distance between superficial and deep aponeurosis, whereas the angle between the visible fascicle length (FL) and deep aponeurosis was indicated as PA. An extrapolated line of visible fascicles between the superficial and deep aponeurosis was drawn to estimate FL.[21,22] Subcutaneous adipose tissue thickness was identified as the line between the skin and muscle interface. A grayscale analysis was used to analyze the raw EI representing muscle quality for the transverse propagational images using ImageJ software. The corrected EI was calculated as the raw EI plus the subcutaneous adipose thickness multiplied by 40.5278.[23] We used averages of two images in the resting and passive test conditions for MT, PA, and FL for further analysis. The intraclass correlation coefficient (ICC) and the coefficient of variation (CV) for BF and MG FLs in the present study were 0.860 [confidence interval (CI): 0.753, 0.911], CV of 5.9%, and 0.936 (CI: 0.898, 0.988), CV of 4.3%, respectively.

For tendon imaging, the cross-sectional area (CSA) of leg tendons was measured in the transverse view using two images of each tendon at the medial malleolus level for the Achilles tendon with the participant prone and their foot placed against the wall.[24] Patellar tendon images were obtained at the midpoint from the tibial tuberosity to the apex of the patella while the participant sat relaxed in a chair with their knee flexed at 90°.[25] An outline of the visible border of each tendon, including the fascia, was digitized manually using the polygon function of ImageJ software to measure the anatomical CSA from the tendon images. We used the average of two images for CSA for further analysis.

2.3.2. Range of motion

SLR was utilized to assess hamstring flexibility. To prevent the initiation of any compensated, counteractive movement (i.e., the posterior pelvic tilt), the contralateral thigh was fixed by a belted strain system in the bed at the pelvis. The tester positioned the inclinometer (bubble inclinometer, Baseline, Fabrication Enterprises, Elmsford, NY, USA) using a foam fixation holder at the distal end of the tibia. At the same time, one hand of the examiner grasped at the back of the calcaneus, and another was placed over the knee to keep it straight. The perception of firm resistance or onset of pelvic rotation was indicated as the end point of passive motion of the hip flexion while participants were lying in a relaxed position.[26] The maximum angle read from the inclinometer was noted at this end point, measured repeatedly 3 times at 15 s intervals. We used averages of the two most closed angles and SLR images for further analysis (ICC 0.932 (CI: 0.902, 0.979), and CV of 2.9%).

For calf ROM assessment, passive DF was measured with the participant lying prone. The examiner first placed the participant's foot in a neutral position (90°) using a standard goniometer (Mahidol University, Bangkok, Thailand), where the stationary arm was parallel with the fibular head, and the movable arm parallel with the lateral side of the foot below the fifth metatarsal and the longitudinal images of MG muscle were also captured for architecture at this initial position (resting condition). Thus, the examiner passively measured the angle of dorsiflexion without rotation or deviations of the participant's foot while the knee was kept straight.[27] The maximum angle read at this point was noted together with the captured longitudinal image of the MG muscle (passive condition) repeated in triplicate at 15 s intervals. We used the average of the two most closed angles and passive DF images for further analysis (ICC 0.889 (CI: 0.810, 0.920), and CV of 4.1%).

2.3.3. Passive joint stiffness

Passive musculotendinous unit (MTU) testing was investigated using a Biodex System 4 isokinetic dynamometer (Biodex Medical Systems, Shipley, New York, USA) with the participant seated on a chair with no shoes, hip flexion at approximately 120°, and shank at 20° below the horizontal setting for knee flexors. Velcro straps were used to stabilize the pelvis and both thighs. The dynamometer axis of rotation was fixed at the right knee joint, and the lever arm pad was attached 2 cm proximally to the malleolus. From the starting position, the dynamometer passively extended the knee 3 times at 5 deg•s^{-1} to the end point of maximum discomfort without pain reported by the participant. As previously prescribed, difficulty in informing a similar end point was observed in participants during a familiarization session.[22] The same maximal end point was determined as the ROM of a trial having a minimal angle compared with the maximal angle averaged at three time points. Using all three data sets from each time point, we then measured the MTU stiffness and the peak resistive torque at the same maximal ROM.

Subsequently, we investigated ankle plantar flexor stiffness while the patient was supine and in a semi-fowler position at 40° without socks and shoes. The examined thigh was flattened and secured on the chair. The level of the lateral malleolus with the straight knee was defined as the axis of ankle rotation.[28] During the measurement, the dynamometer was moved passively toward the ankle at 2 deg•s^{-1} from the 40° plantar-flexed position to the end point of −30° ankle dorsiflexion, repeated in triplicate. We used the average of the peak resistive torque and plantar flexor MTU stiffness measures from the 3 trials at each time point for further analysis.

Passive stiffness in knee flexors and plantar flexors was determined by calculating the slope of the torque-angle relationship within the 50%–80% range of maximum ROM using a least-squares method.[29,30] For knee flexors stiffness, ICC was 0.777 (CI: 0.720, 0.789) with CV of 6.7%, while plantar flexors stiffness showed an ICC of 0.897 (CI: 0.854, 0.967) with a CV of 3.6%. We used surface electromyography to ensure no muscle activities for the rectus femoris, biceps femoris, tibialis anterior, and gastrocnemius muscles.

2.3.4. Eccentric strength

After the passive MTU test, participants were instructed to execute two maximum voluntary eccentric knee flexions with a 1 min break in between them at an angular velocity of 60 deg$\bullet$s^{-1} from a 115° flexed knee position to a 35° extended knee position (where 0° = full knee extension) modified from the previous study,[31] with verbal encouragement throughout the measurement procedure. Then, maximum voluntary eccentric ankle plantar flexions were performed twice at the same angular speed from a 40° plantar-flexed ankle position (shortened) to a 30° dorsiflexed ankle position (lengthened) (protocol adapted from the previous work [32]). We used peak eccentric torque and the angle at peak torque in each muscle for further analysis. In the present study, the intraclass correlation coefficient (ICC) for knee flexor eccentric strength measurement was 0.897 (CI: 0.810, 0.949), and CV was 3.7%. For ankle plantar flexors, the ICC was 0.797 (CI: 0.714, 0.867), with a CV of 6.6%.

2.3.5. Functional performances

A transitional movement ability was measured using the five times sit to stand (5TSTS). This test determines how fast a participant can shift 5 times from a seated to a fully standing posture and back again using a standard chair (43 cm high and 47.5 cm deep). For this and another functional test, a stopwatch (Casio HS-3V, Tokyo, Japan) was used to record the movement time. The chair was located against a wall to prevent it from moving during the test. The test was repeated 3 times at 1 min intervals, and we chose the best time for further analysis.[33]

The TUG test was used to assess functional mobility and balance. The fastest time taken from standing up from a standard chair with a backrest, walking straight for 3 m, turning, and returning to the chair was used for this functional performance test. The test was repeated 3 times at 1 min intervals, and we chose the best time for further analysis.[34]

The 10-m-fast-walk test was assessed to indicate functional mobility and gait performance. Over a 10 m distance, the participant was asked to walk at the quickest pace, and only the middle 3 m of the walk was assessed. The test was performed twice at a 1 min interval. The recorded time was used to convert the walking speed to m$\bullet$s^{-1}. We used the average of the 2 trials for further analysis.[35]

2.4. Home-based interventions

After the baseline measurements, participants received a detailed exercise booklet containing a pre-exercise symptom checklist, exercise procedures, exercise session checklist, and instructions to report any incidence of injury. The first exercise session was closely supervised by a physical therapist at the laboratory to address safety concerns and ensure correct performance of the exercise procedures. Subsequently, the participants were contacted by the investigator once a week remotely via a real-time video call to ensure that the exercise procedures were correctly maintained, and to remind participants to record the amount of exercise and any incidence of injury or adverse effects. In cases where a training session was missed, it was promptly rescheduled for the subsequent day, thereby ensuring participants' completion of the maximum possible number of training sessions throughout the study period.

2.4.1. Dynamic closed-chain stretching

To perform the DCS intervention, a closed kinetic chain hamstring stretching exercise was selected, as described by Chen et al.[31] The participants stood on the involved leg with the knee slightly flexed 10°–15° and were then asked to slowly lean forward until reaching the end of the hip flexion ROM following a standardized 7 min jogging warm-up. At the same time, the contralateral leg was lifted into the hip extension to maintain spine straightness and provide body balance. The participant bent their knee slowly for 1 s down, alternately extending to stretch the hamstring muscles for 1 s. A maximum discomfort without pain felt at the posterior of the thigh was set as the stretch intensity, and less tension was adjusted by decreasing the angle of the trunk leaning forward. This DCS procedure was performed repeatably for 8 repetitions per set in 6 sets with a 15 s rest between sets in both legs, 3 sessions per week, for 6 weeks. The chair's back or the wall was used while they stood on one leg and leaned forward to secure stability for participants in this procedure.

2.4.2. Eccentric exercise

After a standardized 7 min jogging warm-up was completed, a single-leg Romanian deadlift T-drop was initially performed as for the hamstring intervention,[13] as shown in full detail in the booklet provided to the participants. The participants initially stood on the exercised leg with the knee slightly flexed 10°–15° and were then instructed to slowly lean forward until the end of the hip flexion ROM, while the contralateral leg was slowly lifted into the hip extension to maintain a neutral spine position while they slowly returned to their starting position. Second, the strengthening calf exercise was designed using a calf-lowering exercise.[14] Initially, the participant stood on the exercised leg with the contralateral knee flexed at 90°, and then they lifted their body up to a maximum plantar flexion while their hand supported them by its placement on the back of a chair or on a wall. Subsequently, they were instructed to slowly lower their body to the floor while their knee was kept straight. This interventional exercise gradually progressed, as shown in Table 1. Initially, the exercise frequency was set at twice a week to allow participants to adapt to this unfamiliar form of exercise and avoid exercise-induced muscle damage, progressively increasing to three times a week as the weeks advanced.[14] From this particular point, all groups exercised at the same frequency. The participants also performed it every other day to avoid any intentional fatigue with a 1 min rest interval between sets and a 2 min break between exercise legs and the two forms of ECC exercises.

2.4.3. Static stretching

After a standardized 7 min jogging warm-up was performed, participants wrapped a towel under the plantar of the leg to be stretched while relaxed supine. Subsequently, the towel was lifted together with the stretched leg while keeping their knees straight and ankle dorsiflexed. A feeling of the most tension along the posterior of the thigh or hamstrings without pain was defined as the end point of hip flexion motion, and this point was held for 30 s by slightly adjusting the hip angle (i.e., constant torque or tension technique).[30] This exercise was performed 8 times repeatedly with 15 s rest intervals for both sides, again for 3 days per week, for 6 weeks, with a record kept in the booklet provided.

Table 1
The detail of an exercise progression in each exercise for ECC group.

WEEK	DAYS PER WEEK	SETS PER DAY	REPETITIONS PER SET
1	2	2	6
2	2	2	8
3	2	2	10
4	3	3	10
5	3	3	10
6	3	3	10

2.5. Statistical analysis

All descriptive variables were computed and presented as the mean and standard deviation (SD) or the standard error of the mean (SEM). Data were initially tested for normality using a Shapiro–Wilk test. The absolute difference between baseline and post-intervention or 1-month follow-up was given as a mean and 95% confidence interval for comparing exercise protocols. One-way analysis of variance was used to compare all baseline measurements and characteristics between groups. Time, group, and interaction effects were determined using a two-way ANOVA [time (baseline, post, 1-month follow-up) × intervention (DCS, ECC, and ST)], and post hoc multiple comparisons were made using Bonferroni correction for significant interactions. The effect size (ES) was reported as the partial eta-squared for repeated measures (magnitude of effect; small = 0.02, moderate = 0.13, large = 0.26) [36] and as a Cohen *d* where the pairwise comparison was made (small ($d = 0.2$), moderate ($d = 0.5$), and large ($d = 0.8$)).[37] An α level of 0.05 was used to determine significance. All statistical analyses were performed using IBM SPSS Statistics for Windows (version 24.0; IBM Corp., Armonk, NY, USA).

3. Results

3.1. Characteristic variables

The demographic characteristics for each group of nonobese older women aged 60–75 years are shown in Table 2. A one-way ANOVA showed similar baseline characteristics for all dependent variables between the three groups ($p > 0.05$).

The compliance with training was excellent, as all participants completed 100% of the home-based exercise sessions since they were closely monitored and supervised once a week. A few adverse effects were reported following 6 weeks of DCS and ECC interventions, that is, soreness scores of 1.5/10 for back, hamstrings, knees, or calves for 3.5/10 participants in each group.

3.2. The primary outcomes

3.2.1. Hamstring flexibility and knee flexor MTU stiffness

There were no significant differences among groups ($F_{2,48} = 0.1$, $p = 0.927$) (Fig. 2A). After 6 weeks of home-based training, hamstring flexibility measured by passive SLR angle was increased by 14.9% ($p = 0.001$, $d = 0.93$) for the DCS group, 9.2% ($p = 0.042$, $d = 0.66$) for the ECC group, and by 12.3% ($p = 0.005$, $d = 0.81$) for the ST group. This ROM improvement was still present after a 1-month follow-up for all groups ($p < 0.001$) when compared with the pretraining angle. Taken together, there were no significant effects of any intervention on passive knee flexor MTU properties ($F_{2,96} = 1.5$, $p = 0.228$) changes with time (Fig. 2B–D).

3.2.2. Plantar flexors flexibility and ankle plantar flexor MTU stiffness

In the present study, we found no significant group effects on calf flexibility ($F_{2,48} = 2.1$, $p = 0.134$), passive stiffness ($F_{2,48} = 0.4$, $p = 0.705$) or peak resistive torque ($F_{2,48} = 0.8$, $p = 0.471$). In findings similar to those for SLR, there was a improvement in PDF angle after 6 weeks of interventions by 25.9% ($p = 0.003$, $d = 1.08$) for the DCS group, 25.7% ($p = 0.012$, $d = 0.66$) for the ECC group, and by 30.7% ($p = 0.012$, $d = 0.69$) for the ST group (Fig. 3A). A significantly higher passive stiffness after 1 month was found for the ECC group compared with preintervention measurements ($p = 0.04$, $d = 0.54$) (Fig. 3C) and for the ST group ($p = 0.043$, $d = 0.53$) (Fig. 3D).

Table 2
The characteristic of participants in three groups' intervention.

	DCS group (N = 17)	ECC group (N = 17)	ST group (N = 17)	P-values
Age (years)	66.9 ± 3.5	64.6 ± 3.0	66.2 ± 3.4	0.118
Weight (Kg)	52.0 ± 7.9	55.4 ± 5.3	53.7 ± 7.0	0.361
Height (cm)	154.5 ± 5.8	155.6 ± 5.4	156.8 ± 4.0	0.414
BMI ($Kg•m^{-2}$)	21.8 ± 2.8	22.9 ± 1.7	21.8 ± 2.7	0.340

Data are mean and SD. BMI, body mass index.

3.2.3. Leg musculotendinous ultrasound imaging

Leg musculotendinous ultrasound imaging changes in response to the three exercises at each time point are shown in Table 3. There were no significant group or interaction effects for any imaging parameters in the present study ($p > 0.05$). After 6 weeks of home-based training, changes of 13.4% ($p = 0.004$, $d = 0.82$), 19.7% ($p = 0.006$, $d = 0.80$), and 17.9% ($p = 0.041$, $d = 0.56$) in resting BF FL were observed for DCS, ECC (Fig. 4), and ST, respectively. Similarly, a longer resting BF FL was also presented after 1 month of follow-up for DCS and ECC ($p < 0.05$). The lengthening in BF FL was also observed when measured at a stretched position (during SLR) for DCS ($p = 0.042$, $d = 0.54$), ECC ($p = 0.002$, $d = 0.95$), and ST ($p = 0.006$, $d = 0.78$), respectively, following 6 weeks of training. Together with the PA decreased after training interventions ($F_{2,92} = 17.3$, $p < 0.001$, $\eta p^2 = 0.27$). There were no significant substantial changes in the MT and EI of the BF measured at any time point for all groups ($p > 0.05$).

For MG muscle, no alteration of resting MG FL was observed in the present study ($F_{2,96} = 2.8$, $p = 0.063$), whereas a change in MG FL investigated during the PDF test was found for the ECC group ($p = 0.003$, $d = 0.83$) and for the ST group ($p = 0.01$, $d = 0.71$) after 6 weeks of training. No significant alterations in MT or muscle quality of MG were observed as a result of any home-based training program ($p > 0.05$).

There was also no alteration in tendon morphology indicated by CSA in response to exercise interventions for Achilles tendon ($F_{2,96} = 0.1$, $p = 0.951$) and patellar tendon ($F_{2,96} = 0.5$, $p = 0.668$).

3.2.4. Leg eccentric strengths

Eccentric torque as a function of the examined joint angle is shown in Fig. 5. There were no group or interaction effects for knee flexor eccentric torque and angle at peak torque in the present study ($p > 0.05$). For knee flexor function, an increase in peak torque was found after 6 weeks of ECC training ($p = 0.002$, $d = 0.88$) (Fig. 5B) and persisted after 1 month of detraining ($p = 0.003$, $d = 0.84$).

A similar increase in the peak eccentric torque was also seen for ankle plantar flexor muscles in response to calf-lowering training after 6 weeks of ECC training ($p = 0.032$, $d = 0.57$) (Fig. 5E). Notably, there was an interaction with the peak plantar flexor eccentric torque ($F_{4,94} = 3.3$, $p = 0.014$, $\eta p^2 = 0.12$) observed with a two-way ANOVA.

3.3. The secondary outcomes

3.3.1. Functional performances

There were no significant group or interaction effects for any of these functional parameters in the present study ($p > 0.05$). There was a significant time effect on TUG as a result of the exercise interventions ($F_{2,96} = 6.1$, $p = 0.003$, $\eta p^2 = 0.11$). With a post hoc test, the TUG time improved by 0.28 s (CI: 0.02, 0.54 s) ($p = 0.037$, $d = 0.55$) for the DCS group and by 0.62 s (CI: 0.08, 0.73 s) ($p = 0.017$, $d = 0.65$) for the ECC group after 1 month of detraining compared with the pre-measurements. Finally, a significant increase in the fast walking speed was also found after 6 weeks of ECC training, increasing on average 0.10 $m\ s^{-1}$ (CI: 0.01, 0.19 $m\ s^{-1}$) ($p = 0.024$, $d = 0.61$).

4. Discussion

The present study examined whether DCS, ECC, or ST training was effective in improving flexibility and functional capacity in older women when performed at home. The main findings showed that all three

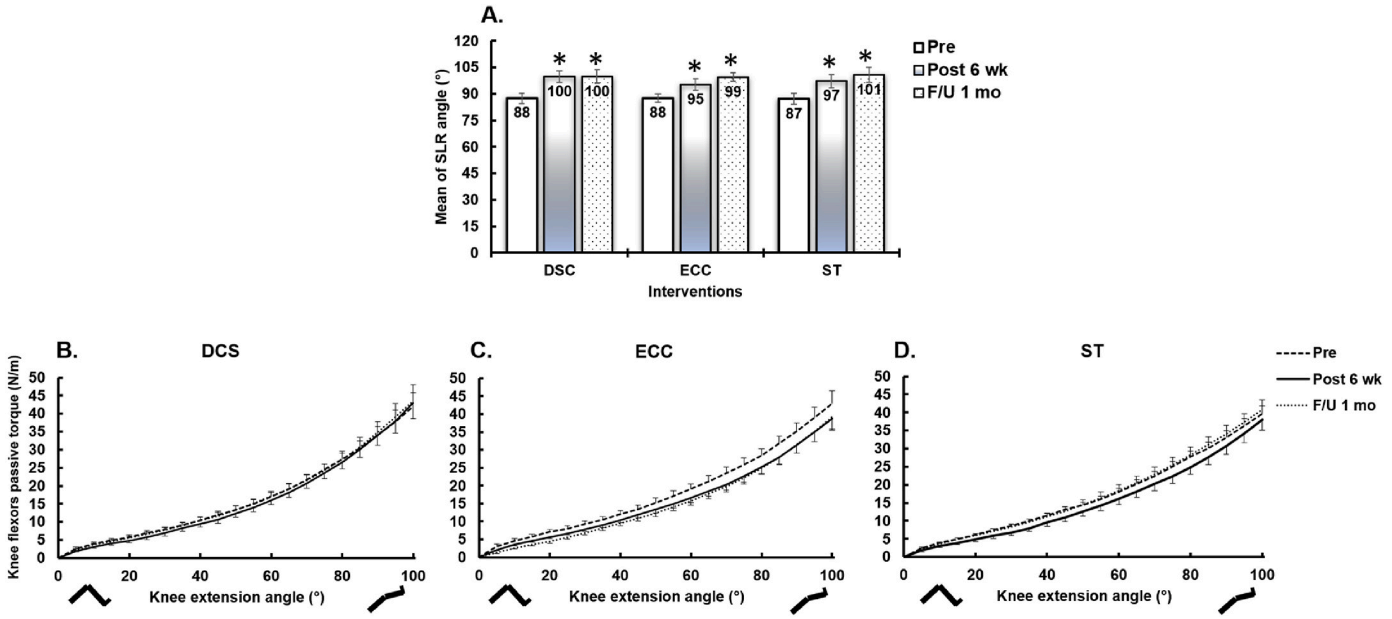

Fig. 2. Effects of 6 weeks of home-based training and detraining for 1 month on the SLR angle and knee flexor MTU passive stiffness. A. Changes in SLR angle. The blank bar is data for preintervention measurement, the shaded bar is for after 6 weeks of training, and the dotted bar is for 1-month follow-up. B–D. Angle–passive torque relationship. The square dotted line is data for preintervention measurement, the solid line is for 6 weeks after training, and the round dotted line is for 1-month follow-up. SLR, straight leg raises; DCS, dynamic closed-chain stretching; ECC, eccentric exercise; ST, static stretching. Data are shown as the mean and SEM ($n = 17$). *Significant difference after exercise intervention compared with baseline ($p < 0.05$).

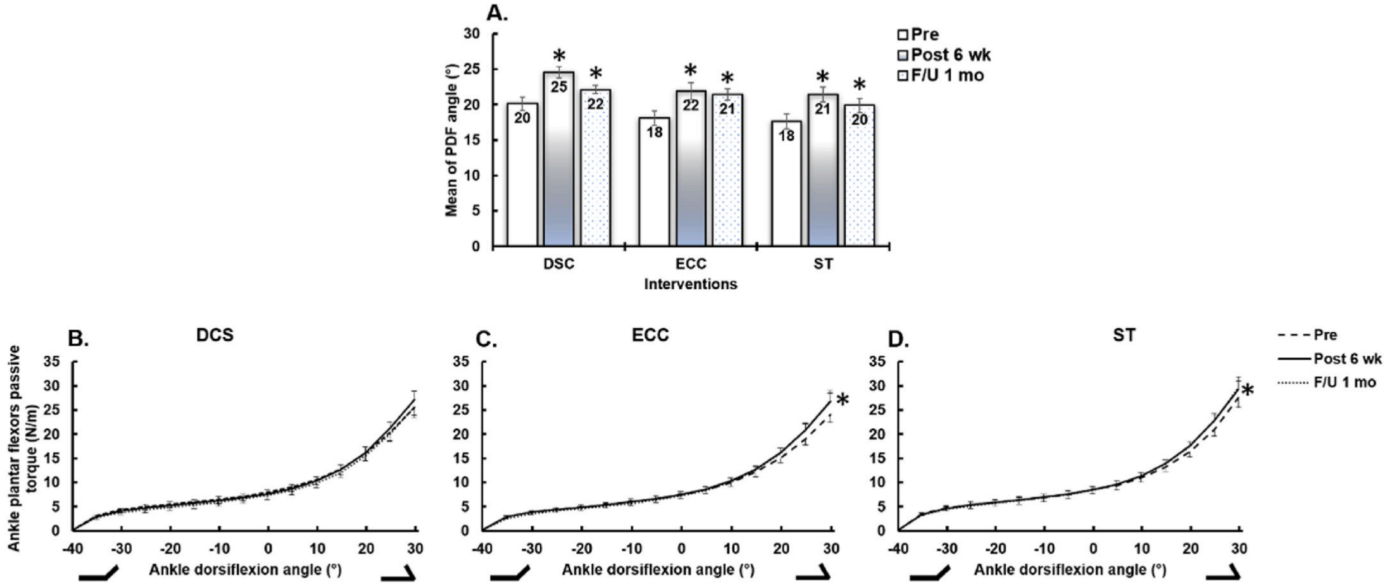

Fig. 3. Effects of 6 weeks of home-based training and detraining for 1 month on PDF angle and ankle plantar flexor MTU passive stiffness. A. Changes in PDF angle. The blank bar is data for preintervention measurement, the shaded bar is for after 6 weeks of training, and the dotted bar is for 1-month follow-up. B–D. Angle–passive torque relationship. The square dotted line is data for preintervention measurement, the solid line is for after 6 weeks of training, and the round dotted line is for 1-month follow-up. PDF, passive ankle dorsiflexion; DCS, dynamic closed-chain stretching; ECC, eccentric exercise; ST, static stretching. Data are given as the mean and SEM ($n = 17$). *Significant difference after exercise intervention compared with baseline ($p < 0.05$).

training programs equally led to a significant increase in leg joint ROM, but ECC training produced greater improvements in leg eccentric strength and fast gait speed than DCS and ST. These results suggest that home-based ECC is more advantageous than either type of stretching in enhancing the physical capacities of older women.

Previous studies have consistently found an improvement in ROM after passive stretching.[38,39] The key observations are that flexibility and eccentric strength training programs resulted in similar increases in ROM, ranging from 9% to 15%, which is higher than the acute changes observed after a single session of these programs (i.e., 6%–8%).[22] A large to moderate increase in SLR angle among participants was due in part to the lengthening of the biceps femoris muscle and a decrease in the muscle's PA. These factors had a greater impact on ROM than MTU compliance, whereas in general, the compliance of knee flexors tended to increase after 6 weeks of home-based eccentric and static stretching training (Fig. 2C and D). It is noteworthy that the plantar flexor MTU demonstrated contrasting outcomes exhibiting increased stiffness rather than enhanced compliance despite similar improvements in passive

Table 3
Musculotendinous ultrasound imaging to represent the changes following 6 weeks of home-based exercise interventions and 1-month detraining (N = 17 per group).

Ultrasound imaging	Group	Pre	Post 6 wk	F/U 1 mo
BF FL_R (cm)	DCS	8.28 ± 2.46	9.26 ± 2.65*	9.47 ± 2.96*
	ECC	8.99 ± 2.78	10.26 ± 3.14*	10.18 ± 3.18*
	ST	8.45 ± 3.00	9.59 ± 3.30*	8.95 ± 2.86
BF FL_P (cm)	DCS	17.73 ± 5.47	19.58 ± 5.82*	20.06 ± 5.81*
	ECC	18.05 ± 5.30	21.03 ± 6.31*	19.86 ± 5.83*
	ST	17.28 ± 5.84	20.57 ± 6.59*	20.92 ± 7.71*
BF PA_R (°)	DCS	10.30 ± 2.10	8.20 ± 1.80*	9.00 ± 2.30*
	ECC	9.80 ± 2.70	8.20 ± 2.10*	7.90 ± 2.10*
	ST	10.80 ± 3.60	9.10 ± 2.30*	10.10 ± 3.00
BF PA_P (°)	DCS	3.80 ± 1.20	2.60 ± 1.50*	2.80 ± 1.20*
	ECC	3.80 ± 1.00	2.50 ± 1.20*	2.30 ± 1.20*
	ST	4.00 ± 2.10	3.50 ± 1.60	2.90 ± 1.40*
BF MT_R (cm)	DCS	1.46 ± 0.41	1.50 ± 0.46	1.53 ± 0.41
	ECC	1.49 ± 0.41	1.57 ± 0.45	1.53 ± 0.44
	ST	1.47 ± 0.44	1.51 ± 0.48	1.61 ± 0.46
BF MT_P (cm)	DCS	1.58 ± 0.46	1.62 ± 0.46	1.61 ± 0.45
	ECC	1.60 ± 0.45	1.58 ± 0.45	1.59 ± 0.44
	ST	1.58 ± 0.46	1.62 ± 0.44	1.61 ± 0.46
BF EI (A.U.)	DCS	68.50 ± 8.40	66.80 ± 11.50	71.90 ± 9.30
	ECC	65.80 ± 8.10	66.00 ± 10.00	63.90 ± 9.40
	ST	67.50 ± 11.30	67.30 ± 11.80	66.40 ± 10.90
BF ST (cm)	DCS	0.95 ± 0.31	1.00 ± 0.28	0.99 ± 0.28
	ECC	0.97 ± 0.27	1.03 ± 0.32*	1.03 ± 0.32
	ST	0.83 ± 0.31	0.85 ± 0.26	0.87 ± 0.31
MG FL_R (cm)	DCS	4.42 ± 1.20	4.52 ± 1.23	4.60 ± 1.20
	ECC	4.53 ± 1.17	4.75 ± 1.26	4.73 ± 1.24
	ST	4.49 ± 1.15	4.64 ± 1.23	4.56 ± 1.17
MG FL_P (cm)	DCS	5.53 ± 1.40	5.51 ± 1.47	5.66 ± 1.42
	ECC	5.58 ± 1.42	5.85 ± 1.47*	5.85 ± 1.57
	ST	5.40 ± 1.38	5.69 ± 1.49*	5.64 ± 1.51
MG PA_R (°)	DCS	19.50 ± 2.50	18.30 ± 2.60	17.40 ± 2.50*
	ECC	19.90 ± 2.50	18.90 ± 2.20	19.00 ± 2.40
	ST	19.40 ± 2.60	17.20 ± 2.80*	18.40 ± 2.30
MG PA_P (°)	DCS	16.50 ± 1.90	16.80 ± 2.80	15.70 ± 1.80
	ECC	17.10 ± 1.50	17.20 ± 2.10	16.90 ± 2.40
	ST	16.70 ± 2.50	15.60 ± 2.60	16.40 ± 2.40
MG MT_R (cm)	DCS	1.41 ± 0.40	1.390 ± 0.40	1.35 ± 0.40
	ECC	1.50 ± 0.39	1.49 ± 0.38	1.50 ± 0.40
	ST	1.43 ± 0.39	1.35 ± 0.37	1.40 ± 0.39
MG MT_P (cm)	DCS	1.53 ± 0.42	1.52 ± 0.42	1.50 ± 0.42
	ECC	1.63 ± 0.42	1.62 ± 0.41	1.64 ± 0.43
	ST	1.50 ± 0.40	1.45 ± 0.38	1.51 ± 0.40
MG EI (A.U.)	DCS	62.00 ± 10.30	60.50 ± 10.20	66.30 ± 9.10
	ECC	57.60 ± 11.10	62.40 ± 9.60	61.30 ± 12.50
	ST	60.80 ± 8.90	63.60 ± 8.00	62.70 ± 8.20
MG ST (cm)	DCS	0.73 ± 0.21	0.72 ± 0.18	0.76 ± 0.19
	ECC	0.76 ± 0.13	0.79 ± 0.21	0.82 ± 0.18*
	ST	0.69 ± 0.17	0.71 ± 0.16	0.74 ± 0.17
AT CSA (cm^2)	DCS	0.51 ± 0.11	0.51 ± 0.13	0.51 ± 0.11
	ECC	0.53 ± 0.11	0.53 ± 0.10	0.54 ± 0.13
	ST	0.56 ± 0.13	0.57 ± 0.14	0.56 ± 0.14
PT CSA (cm^2)	DCS	0.73 ± 0.08	0.71 ± 0.07	0.72 ± 0.09
	ECC	0.75 ± 0.15	0.73 ± 0.12	0.73 ± 0.12
	ST	0.70 ± 0.14	0.73 ± 0.15	0.74 ± 0.18

Data are mean and SD. DCS, dynamic closed-chain stretching; ECC, eccentric exercise; ST, static stretching; BF, biceps femoris; MT, muscle thickness; PA, pennation angle; FL_R, resting fascicle length; FL_P, fascicle length during passive test; EI, echo intensity; ST, subcutaneous thickness; MG, medial gastrocnemius; AT, Achilles tendon; CSA, cross sectional area; PT, patellar tendon. *Significant change from pre-exercise ($p < 0.05$).

ROM for the plantar flexors and knee flexors. This may be attributed to an increase in tendon or connective tissue stiffness rather than a muscle property, as the overall MTU stiffness was found to be reduced without concomitant adaptations in muscle FL.[40] However, further investigation is required to confirm this hypothesis. It should be noted that DCS and ST exercises at home in the present study were performed to obtain hamstring stretching and are also likely to transfer substantial stress on the posterior chain of the lower extremities down to the calf muscle, thus also increasing the passive DF angle. Moreover, the increase in ROM was not always accompanied by fascicle lengthening, suggesting that other mechanisms, such as increased stretch tolerance,[41,42] also contributed considerably to the outcomes of the training. We found that the ROM improvement persisted even after 1 month of follow-up, which is consistent with previous studies reporting the retention of ROM improvements for up to 4 weeks after detraining.[42]

Both static stretching and eccentric training can lead to increases in FL.[13,43–45] The changes in muscle fiber length are associated with myofibrillar remodeling, which results in the formation of new sarcomere structures. This phenomenon occurs mainly after lengthening exercises and is more pronounced following eccentric-type exercises, wherein the muscle is subjected to forceful lengthening. The aforementioned findings are supported by studies in humans and animals.[44,46,47] However, the extent to which eccentric training can promote these adaptations has not been as extensively examined. In the present study, a slightly greater effect of intervention for BF was seen when measuring FL at longer muscle length compared with resting FL, and for MG change was observed only in lenghthened muscle position. For instance, BF FL increased by approximately 0.67 cm at rest, similar to findings in young adults after 6 weeks of eccentric hamstring training at long-muscle length.[48] Moreover, FL_P showed a substantial 1.74 cm change following 6 weeks of home-based eccentric training in this study. Similar findings have also been reported by Kellis[49] in which a higher FL of hamstring elongation is seen at longer muscle lengths. To emphasize this point and enhance data accuracy, it is recommended to assess fascile length subsequent to these exercises at lengthened muscle.

The present study found that there were no alterations in MT, EI, or tendon morphology as a result of either the stretching or eccentric home-based training programs. This outcome is predictable because the loading intensity was not sufficiently high to induce adaptations in musculotendinous morphology. Previous studies, such as those by Douglas and Križaj with colleagues [50,51] have indicated that heavy ECC training is particularly effective in promoting muscle hypertrophy. A recent review also suggests that training the Achilles tendon with high-magnitude loading for more than 12 weeks can elicit better tendon adaptation in healthy and pathological tendon tissue.[52] To maximize loading on the Achilles tendon, weight-bearing exercises are recommended, particularly at large ankle dorsiflexion, knee extension, and hip extension positions, or perhaps with the use of additional resistance.[52] The absence of any changes in muscle quality, as defined by EI, after 24 months of resistive and endurance exercises has also been reported, and it was suggested that this lack of change was due to the training intensity.[53] However, a higher EI was not found in this study because no change in the muscular component for intramuscular adipose tissue or fibrous tissue occurred [18] as a result of our training program.

Implementing an eccentric training program at home can lead to significant improvements in the eccentric peak torque of knee flexors and ankle plantar flexors. After a 6-week intervention period, knee flexors exhibited a 21.5% increase in strength, which persisted beyond the training period. It is notable that increased activation of agonist and synergist muscles and fiber hypertrophy are suggested to be involved in the improvement of eccentric strength as a result of ECC training.[12] Additionally, this type of exercise resulted in a significant increase in fast walking speed, whereas stretching programs did not. We found a moderately increased speed of 0.10 m s^{-1}, which is considered to be clinically important.[54,55] Older adults with a high fall risk tend to walk at a slower pace compared to those with a lower fall risk.[56] Moreover,

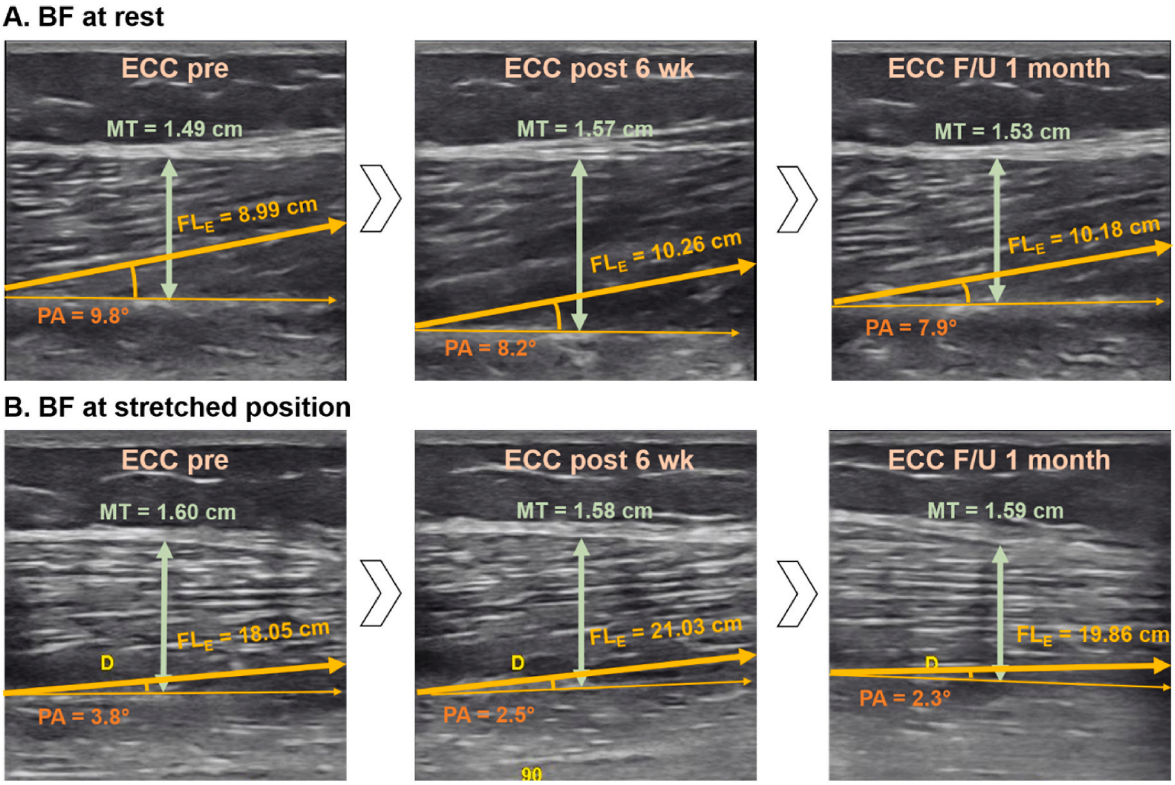

Fig. 4. Example thumbnail images of BF muscle architecture for mean results analysis measured at rest and in a stretched position during the SLR test following home-based ECC intervention and at 1 month of detraining. BF, biceps femoris; ECC, eccentric training; MT, muscle thickness; PA, pennation angle; FL_E, extrapolated fascicle length. Data are given as the mean (n = 17).

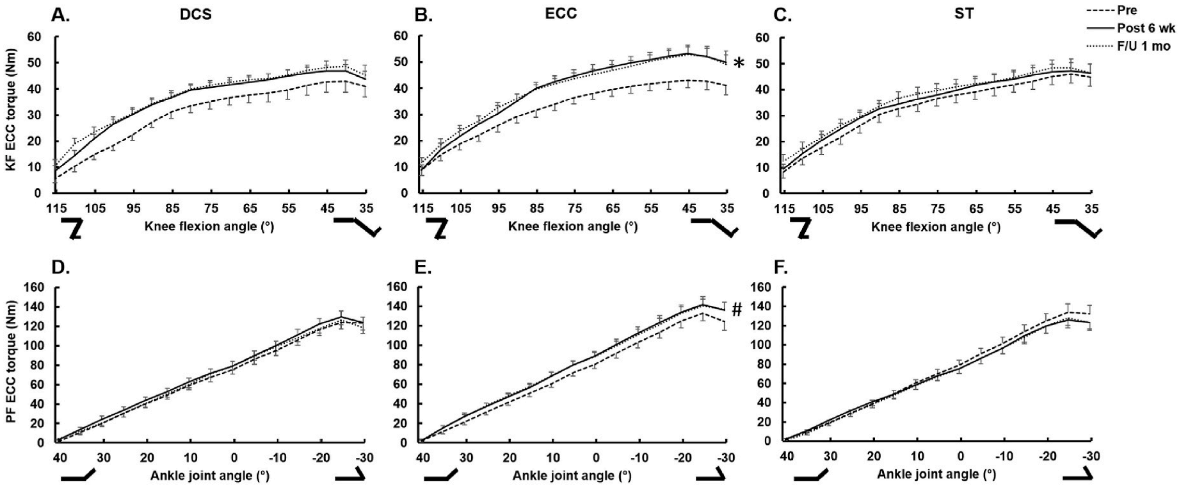

Fig. 5. Angle torque relationships during eccentric contraction of the knee flexors (A–C) and ankle plantar flexors (D–F). The square dotted line is data for pre-intervention measurements, the solid line is for after 6 weeks of training, and the round dotted line is for 1 month of follow-up. DCS, dynamic closed-chain stretching; ECC, eccentric exercise; ST, static stretching. Data are shown as the mean and SEM (n = 17). *Significant difference after exercise intervention at 6 weeks and at 1 month after detraining compared with the baseline. #Significant difference after exercise intervention at 6 weeks compared with the baseline ($p < 0.05$).

recent research supports that the combination of a decline in gait speed along with memory decline exhibits the strong association with dementia risk in older adults.[57] The findings are consistent with those of previous studies,[58] which support the notion that eccentric exercise may have beneficial effects on mitigating the decline in eccentric muscle strength and mobility in older adults. Earlier investigations suggest that ECC exercise also confers benefits such as better balance, decreased incidence of falls, increased mobility and power, greater satellite cell response, improved endurance, and enhanced quality of life in older adults.[15,59,60] Furthermore, the compliance of older women with the eccentric program was excellent, and the exercise can be performed safely and easily at home without requiring any equipment, making it a primary option for preserving and improving the physical and functional capacities of this older population. Moreover, dynamic stretching training also showed a trend toward increased eccentric strength in older women, as previously observed in young women,[61] and alternating eccentric training with unilateral-leg DCS exercises may represent an alternative to enhance flexibility and muscle strength in older people.

It was unexpected that these nonobese older women did not show any improvement in balance and functional capacity, as assessed by the 5TSTS and TUG tests, after undergoing 6 weeks of ECC or DCS training with a unilateral-leg stance and natural body weight. This finding contradicts those of a previous study by Katsura et al.[14] which found improvements in chair stand and TUG after 8 weeks of home-based ECC training. This suggests that other targeting specific muscle groups, such as knee and hip extensors, may be necessary to improve functional performance. However, there was a slight improvement in TUG time observed during the 1-month follow-up for both the ECC and DCS groups, which may be attributed to a learning effect, despite the participants undergoing familiarization sessions. It is important to note that the participants in this study were physically active, had BMI in their normal range, and had relatively good baseline performance on the tests, which suggests that the effects of the training programs may be limited for this specific population. Future studies may be needed to determine alternative training strategies that are tailored to the individual needs of less physically fit older women. Overall, the present findings highlight the importance of considering individual characteristics and training needs when designing exercise programs for older adults to optimize their functional performance and quality of life.

The primary challenges encountered was the difficulty in achieving a perfect match in exercise volume across all interventions. Due to differences in the nature of the interventions, such as static stretching requiring a longer time than dynamic closed-chain stretching, it was not possible to equalize the exercise volume completely. This is a common issue when comparing interventions directly. Another challenge in this type of research lies in the limited control over the subjects' movements technique and exercise intensity when performed at home, despite recording high compliance rates. Finally, the results of the present study are limited to older women with non-hamstring tightness. Therefore, future studies should aim to address this imbalance and focus on older men with muscle tightness, as they are likely to exhibit less flexibility than women.[62]

5. Conclusion

The present research indicates that dynamic closed-chain stretching, eccentric exercise, and static stretching training programs conducted at home are effective in enhancing flexibility in older women. Nonetheless, eccentric training surpasses both stretching programs because it leads to a broader range of advantages for the physical abilities of older adults, such as enhancements in leg eccentric strength and fast gait speed. The study highlights the prospective importance of integrating home-based eccentric muscle training into physical activity plans that are intended to enhance functional capacity in older women.

Author contributions

Conceptualization, P.M., J.N. and S.K.; methodology, P.M.; formal analysis, P.M., W.S.; investigation, P.M., J.N., K.B; data curation, P.M., A.S.; writing—original draft preparation, P.M., K.B.; writing—review and editing, P.M., J.N., W.S., S.K.; supervision, P.W.; project administration, P.M.; funding acquisition, P.M. All authors have read and agreed to the published version of the manuscript.

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Data availability statement

Not applicable.

Declaration of competing interest

The authors declare no conflict of interest.

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