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Enhancing prehension strength and dexterity through cross-education effects in the elderly

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Cross-education, the enhancement of an untrained limb following training of the opposite limb, encompasses both strength and dexterity—a vital factor in daily activities. In the elderly, where both strength and dexterity decline, investigating the simultaneous transfer of these attributes through motor training is crucial. This study explored the effects of a novel hand training program on prehension strength and hand dexterity in the elderly (> 65 years). Maximum Grasping Force (MGF), Jebsen–Taylor hand function test, and Purdue Pegboard test were measured. Training, focusing on 20% sub-maximal force control, occurred thrice weekly for five weeks. Post-training, improvements were observed in both MGF and hand function in both hands, indicating the efficacy of the program. Simultaneous inter-limb transfer effects in strength and dexterity support the potential of cross-education for hand rehabilitation in elderly or hemiparetic patients. This study contributes insights into optimizing interventions for enhancing strength and dexterity in the elderly.

Cross-education (CE) is a captivating phenomenon that encompasses unilateral limb training leading to performance enhancement in the contralateral untrained limb[1,2]. While prior research has predominantly focused on its effects on muscle strength[3,4], CE's influence also extends to motor skill acquisition[5,6]. This inter-limb transfer of motor performance is underpinned by shared mechanisms that include neuroplasticity in the primary motor cortex (M1)[7], neural adaptations within motor areas[8,9], and cross-activation between brain hemispheres[6]. The importance of CE transcends scientific intrigue and has practical applications, particularly concerning the challenges of aging in the elderly. Deterioration in dexterity and strength is a significant concern affecting their quality of life[10]. These attributes are fundamental to activities of daily living, encompassing tasks such as eating, dressing, grooming, and object manipulation, making it imperative to explore the potential of CE in enhancing these essential functions.

Aging leads to changes in the neuromuscular system, resulting in diminished prehension strength and manual dexterity[11]. The necessity for interventions to counteract age-related deterioration becomes apparent. Strategies like resistance training[7,12] and motor skill acquisition[13] have been proposed to mitigate the consequences of aging on gross and fine motor control. Daily hand tasks necessitate both finger strength and dexterity[14], and these attributes are indispensable for everyday activities. Prior research[15,16] has demonstrated that training designed to increase muscle strength can concurrently lead to improvements in motor function. These findings suggest the promise of a unified training regimen for bolstering both muscle strength and motor function, offering a valuable approach for individuals grappling with impaired physical function, particularly the elderly.

As our understanding of aging evolves, the need for innovative approaches to enhance hand control in the elderly becomes increasingly evident. Game-based training trainings (GBGT), inspired by gamification principles, offer a promising avenue for improving hand function. Prior research[17,18] has demonstrated that gamified approaches can significantly improve hand strength and dexterity by engaging participants and promoting adherence to training regimens. Our program builds on these findings by incorporating key features of traditional hand training protocols[13,19–21]—such as precise grip control, task-specific practice, and repeated

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force production—into an interactive and engaging game-based framework. This novel approach ensures a rigorous training program designed to challenge motor control skills while maintaining participant motivation. By combining principles of motor learning with gamification, this study introduces a unique method for addressing age-related declines in hand function.

Importantly, CE offers therapeutic potential[2,22] due to its positive influence on muscle strength[3,23], hand grip[21,24], and motor function[25,26], positioning it as a promising strategy for addressing age-related physical decline. Prior studies[27,28] have indicated that CE remains effective in the elderly, consistently manifesting its transfer effects despite the impact of age-related changes. The elderly often experiences CE effects, a consequence of over-activation compensatory mechanisms[29–31], which aid in preserving motor function in the face of age-related neurobiological changes. Yet, the potential CE effect's influence on both strength and dexterity remains predominantly uncharted.

Consequently, this study aims to answer specific questions: Can training enhance strength and manual dexterity in the elderly while inducing the transfer of these effects to the untrained limb? Previous studies[20,32,33] have challenged the 'strength-dexterity trade-off hypothesis', providing evidence that strength training can enhance dexterity rather than diminish it. These findings lead to the possibility of potential for concurrent improvements in strength and fine motor control, particularly in the elderly. Thus, further exploration is required to validate this complementary relationship, especially in the context of aging-related neuromuscular decline.

Our study builds on this evidence by introducing a game-based hand training protocol designed to enhance both prehension strength and manual dexterity. This investigation aims to further examine the hypothesis of a 'strength-dexterity complementary relationship', specifically within the elderly. We have investigated whether prehension strength and manual dexterity undergo modifications following novel hand training of the dominant hand in the elderly, and whether this training successfully triggers CE effects for both aspects. Our hypothesis posits that a GBGT would enhance both prehension strength and manual dexterity in the trained and untrained hands within the elderly, demonstrating the potential for cross-limb improvements in motor performance. The study delves into the intriguing possibility that improvements in both strength and dexterity may coexist in the elderly. This current has the potential to substantially enhance our understanding of CE's impact on the elderly, while also offering innovative strategies to enrich their quality of life.

Materials and methods

Participants

Twenty-five healthy elderly women participated in this study: the training group consisted of eleven participants (age: 73.92 ± 5.47 years, height: 152.1 ± 4.55 cm, weight: 55.6 ± 8.45 kg), while the control group included fourteen participants (age: 73.85 ± 2.79 years, height: 153.43 ± 6.76 cm, weight: 58.42 ± 8.87 kg). The participants were randomly assigned to either the training group or the control group, with no significant differences in age, height, or weight observed between the two groups. All participants were members of the Seoul Metropolitan Gwangjin Senior Welfare Center in Seoul, Korea. All participants were right-handed, as determined by the Edinburgh Handedness Inventory[34]. None of the participants had a history of neuropathies, traumas, or arthritis affecting their upper extremities. The study was approved by the Hanyang University Institutional Review Board (HYI-12-044-Comp2). The research was performed in accordance with relevant guidelines and regulations. Informed consent was obtained from all participants.

Experimental set-up

We employed a customized handle equipped with five force sensors (FUTEK Advanced Sensor Technology, Inc., CA, USA; grip width: 60 mm) for measuring maximal grasping force (MGF) and implementing a game-based grasping training (GBGT) (Fig. 1). The sensors' vertical positions were adjustable to align with natural digit locations during grasping, ensuring a grip width of 60 mm for each participant. A custom software, developed using LabVIEW (LabVIEW 8.2, National Instruments Corporation, Austin, TX), facilitated the GBGT (refer to the Training section below for protocols). For MGF measurement, the same handle was utilized, and a distinct LabVIEW software was designed for accurate measurement.

Experimental design

In the current study, all participants underwent a prehension strength test (maximal grasping force (MGF)) and two clinical hand function tests (Jebsen–Taylor hand function test (JT) and Purdue Pegboard test (PB)). Measurements were taken at three intervals: before training (Pre-test), 5 weeks after the pre-test (Post-test), and 2 weeks after the post-test (Retention-test). The 2-week interval between the post-test and retention test was chosen based on prior research demonstrating that this period is sufficient to assess the retention of motor skills and training effects[35].

This study included a control group to ensure that improvements in prehension strength and dexterity could be attributed to the GBGT intervention and not to confounding factors such as test familiarization or practice effects from repeated measurements. The control group participants were only called to the lab for pre-, post-, and retention-test sessions and did not participate in any training sessions or additional visits. This design allowed us to isolate the effects of the intervention and strengthen the study's internal validity.

The inclusion of the control group enabled a direct comparison to the training group, ensuring that observed improvements in the training group could be confidently attributed to the GBGT intervention. By limiting the control group's participation to testing sessions only, we minimized potential practice effects or other influences, providing a robust baseline for evaluating the intervention's effectiveness.

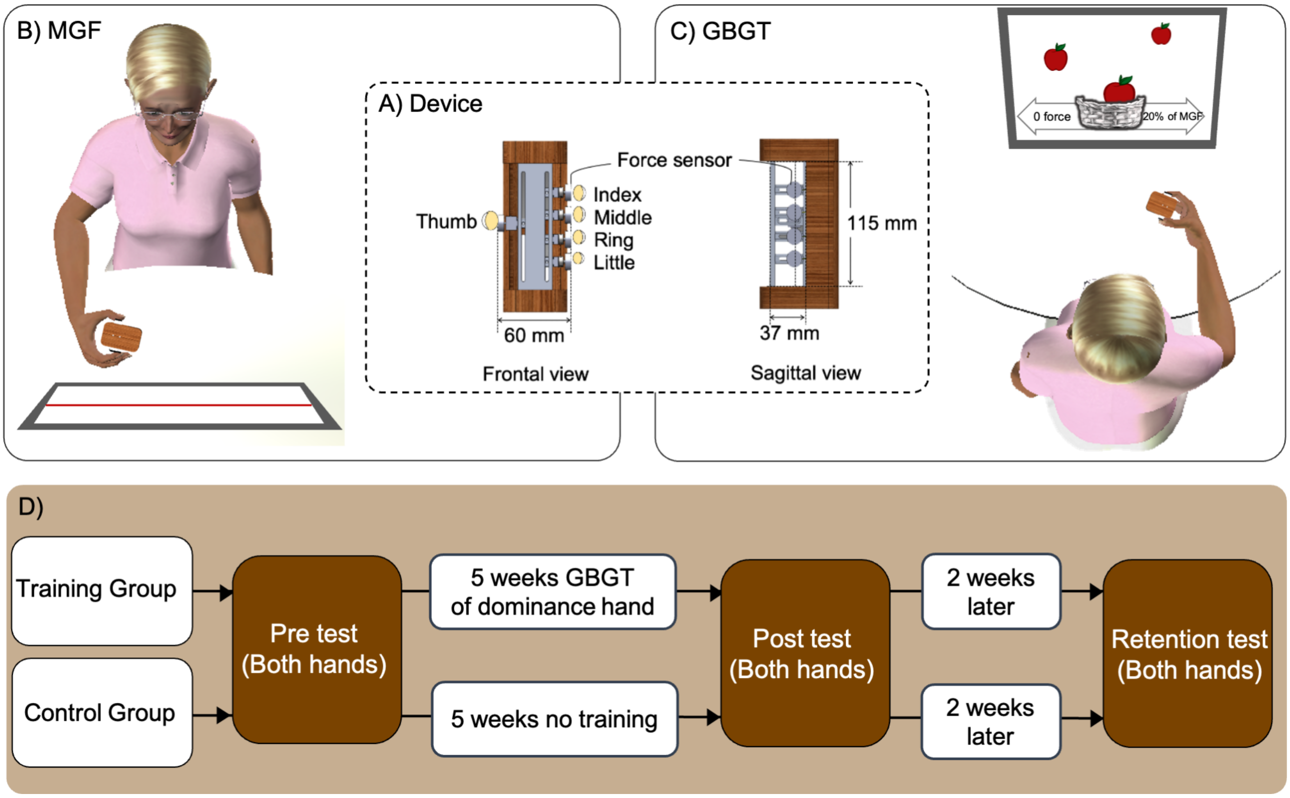

Fig. 1. The experimental settings for both groups. (**A**) Five sensors were attached to a grip type device. The participant holds a handle with individual fingers positioned on each sensor. (**B**) The participant measures the Maximum grasping force of dominant and non-dominant hand using a device. (**C**) The set-up for the Game-Based Grasping Training for the dominant hand. The hand, wrist and forearm were immobilized with a band. The participant watched the computer screen to perform a task while sitting in a chair. (**D**) The experiment process flow chart. Participants performed tests three times before training, post-test after 5 weeks, and retention- test after 2 weeks. All tests included MGF and two clinical tests (i.e., Jebsen–Taylor hand function test and Purdue Pegboard test). Drawn using Poser Pro 11 (www.posersoftware.com) and Microsoft Office 2019 (www.microsoft.com).

Procedures

For the MGF test, a grip-type handle was utilized (Fig. 1A). Participants sat on a chair, maintained a comfortable sitting position, and rested their measuring forearm on a table. Facing a monitor with an elbow flexed at approximately 90 degrees, they kept their wrist in a neutral position. An instructor controlled their posture to prevent wrist supination and pronation. Participants were instructed to grasp the handle with the thumb and four fingers together, exerting maximal force for 5 s. A horizontal bar on the screen provided force feedback. Two trials were conducted for each hand with a 1-min interval between tests to minimize fatigue[19].

Clinical hand function tests were conducted according to the following procedure. The JT evaluated various hand activities and overall upper limb function, consisting of seven tasks. Excluded was the writing test to eliminate experimental error. The PB assessed overall movement and manual dexterity of the hand[36]. Both tests were performed on both dominant (right) and non-dominant (left) hands.

The GBGT involved participants from the training group. This training consisted of controlling the force exerted on sensors of a grip-type handle. While seated comfortably, they faced a screen providing force feedback and manipulated a basket that moved horizontally. During the training sessions, all participants maintained their non-training limb relaxed and naturally extended to the side of their body. This position was maintained throughout the training period to ensure that the non-training limb did not engage in any activity, such as passive movement or isometric exercise, which could confound the results. Participants controlled a basket to catch descending objects (apples) by exerting precise grip force with the thumb and four fingers. They maintained 20% of their individual MGF using their dominant hand, a level chosen to challenge fine motor control without inducing fatigue[19,37]. The training integrated isometric force control and task-specific practice into a game-based framework with real-time feedback to enhance motor learning. Each session lasted 10 min with rest periods to sustain engagement and performance. Unlike traditional methods, this dynamic program utilized progressive and variable tasks to target grip precision and adaptability, making it engaging and effective for elderly participants.

Data analysis

MGF was quantified as the peak magnitude generated by the thumb and four fingers during the grasping task. The peak magnitude was determined by summing the values recorded from each of the five individual sensors, which measured the forces exerted by the thumb and each finger, respectively. MATLAB (MathWorks, Natick, MA, USA) was employed for all data processing. For the JT, the results of the six tasks, measured in time (seconds) for each test (excluding writing), were standardized using the Korean scoring system for JT. The PB performance was determined by the average number of pegs inserted over three 30-s trials. The results for all participants were normalized by calculating their values relative to the mean value obtained during the pre-test for each test.

Statistics

A two-way repeated-measures ANOVA was conducted using SPSS (Version 29.0; IBM Corp., Armonk, NY, USA) with the within-subjects factor of TEST (with three levels: pre-test, post-test, and retention-test, spaced at 5-week intervals between pre- and post-test and 2-week intervals between post- and retention-test) and the between-subjects factor of GROUP (with two levels: training group and control group). Statistical significance was set at $p < 0.05$, and Bonferroni corrections were applied for multiple comparisons where appropriate.

Results

We conducted assessments on MGF for measuring prehension strength, JT test, and PB test to evaluate manual dexterity in elderly participants. Following the training, significant improvements were observed in both MGF and hand functions (JT and PB) for both the dominant (trained) and non-dominant (untrained) hands. All the results were represented as normalized data by calculating the values relative to the mean values obtained in the pre-test.

Maximal grasping force (MGF)

In the dominant hand, the training group displayed a notable increase in MGF, while the control group showed relative stability (Fig. 2A). Significant improvements were evident between the pre- and the post-test and between the pre- test and the retention- test. These results highlight the training's effectiveness in enhancing and maintaining grip strength. A two-way repeated-measures ANOVA revealed a significant TEST effect [$F_{(1,23)} = 8.175$, $p < 0.001$, $\eta^2 = 0.262$] and GROUP x TEST interaction [$F_{(1,23)} = 5.105$, $p = 0.01$, $\eta^2 = 0.182$], with non-significant GROUP effects. Post-hoc comparisons indicated a significant increase in MGF for the training group from the pre-test to the post-test ($p = 0.006$) and from the pre-test to the retention- test ($p < 0.001$), whereas no significant difference was observed between the post-test and the retention- test.

In contrast, MGF for the control group did not exhibit significant changes. Figure 2B revealed a significant increase in MGF after training in the non-dominant hand. The training group exhibited a notable increase

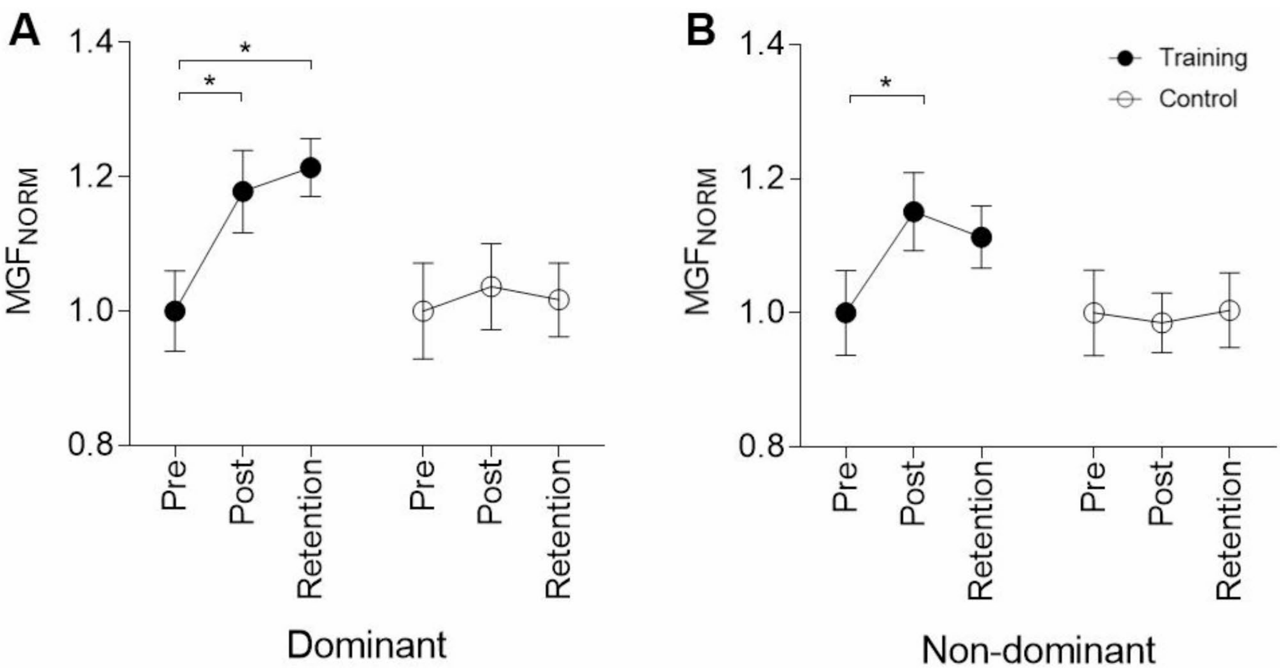

Fig. 2. The results of prehension strength test for the training and control group. (**A**) Maximal Grasping Force (MGF) values in the dominant hand during pre-, post-, and retention- test. (**B**) MGF values in the non-dominant hand during the pre-, post-, and retention- test. The black dots represent the training group, and the empty dots represent the control group. All the MGF results were represented as normalized data by calculating the values relative to the mean values obtained in the pre-test (MGF_{NORM}). *signifies significant ($p < 0.05$) differences in MGF among the tests.

between the pre-test (1 ± 0.22) and the post-test (1.15 ± 0.20). This result suggests that dominant hand training contributed to the improvement of non-dominant hand grip strength. These findings were supported by a significant GROUP x TEST interaction [$F_{(1,23)} = 4.037$, $p = 0.024$, $\eta^2 = 0.149$], with non-significant TEST and GROUP effects. Post-hoc comparisons indicated a significant increase in MGF for the training group from the pre-test to the post-test ($p = 0.019$), while no significant difference was observed between the post-test and the retention- test. In contrast, MGF for the control group did not change significantly.

Effects of training of manual dexterity

Jebsen Taylor hand function test (JT)

The dominant hand function improved in the training group, while it did not change in the control group, which were evidenced by JT scores (Fig. 3A). These findings were supported by a two-way repeated-measure ANOVA, which showed the significant TEST effect [$F_{(1,23)} = 8.490$, $p < 0.001$, $\eta^2 = 0.270$], GROUP effects [$F_{(1,23)} = 14.503$, $p < 0.001$, $\eta^2 = 0.387$] and GROUP x TEST interaction [$F_{(1,23)} = 13.283$, $p < 0.001$, $\eta^2 = 0.366$]. Post-hoc comparisons revealed that JT scores significantly decreased from the pre-test to the post-test ($p < 0.001$) and from the pre-test to the retention-test ($p < 0.001$). However, there was no significant difference between the post-test and retention- test ($p = 0.13$). In non-dominant hand, the training group showed a significant change in JT scores, whereas the control group indicated relatively stable JT scores. (Fig. 3B). The results indicated that the significant TEST effect [$F_{(1,23)} = 15.545$, $p < 0.001$, $\eta^2 = 0.403$], GROUP effects [$F_{(1,23)} = 14.648$, $p < 0.001$, $\eta^2 = 0.389$] and GROUP x TEST interaction [$F_{(1,23)} = 31.131$, $p < 0.001$, $\eta^2 = 0.575$]. Post-hoc analysis revealed a significant decrease in JT scores from the pre-test to both the post-test and the retention- test ($p < 0.001$), while no significant difference was found between the post-test and the retention- test ($p = 0.08$). These results indicate that the training group demonstrated greater performance improvements compared to the control group.

Purdue peg board test (PB)

In the dominant hand, the training group exhibited improved hand function, while the control group showed no significant change, as indicated by PB scores (Fig. 4A). These findings were supported by a two-way repeated-measure ANOVA, which demonstrated significant TEST effects [$F_{(1,23)} = 4.028$, $p = 0.024$, $\eta^2 = 0.149$], GROUP effects [$F_{(1,23)} = 5.391$, $p = 0.029$, $\eta^2 = 0.190$] and GROUP x TEST interaction [$F_{(1,23)} = 9.555$, $p < 0.001$, $\eta^2 = 0.293$]. Post-hoc comparisons revealed a significant increase in PB scores for the training group from the pre-test to the post-test ($p < 0.001$) and from the pre-test to the retention- test ($p < 0.001$), whereas no significant difference was observed between the post-test and the retention- test. In contrast, PB scores for the control group did not change significantly. In the non-dominant hand, the training group exhibited a significant change in PB scores, whereas the control group indicated relatively stable PB scores (Fig. 4B). These findings were supported by significant TEST effects [$F_{(1,23)} = 4.789$, $p = 0.013$, $\eta^2 = 0.172$], GROUP effects [$F_{(1,23)} = 3.037$, $p = 0.095$, $\eta^2 = 0.117$], and

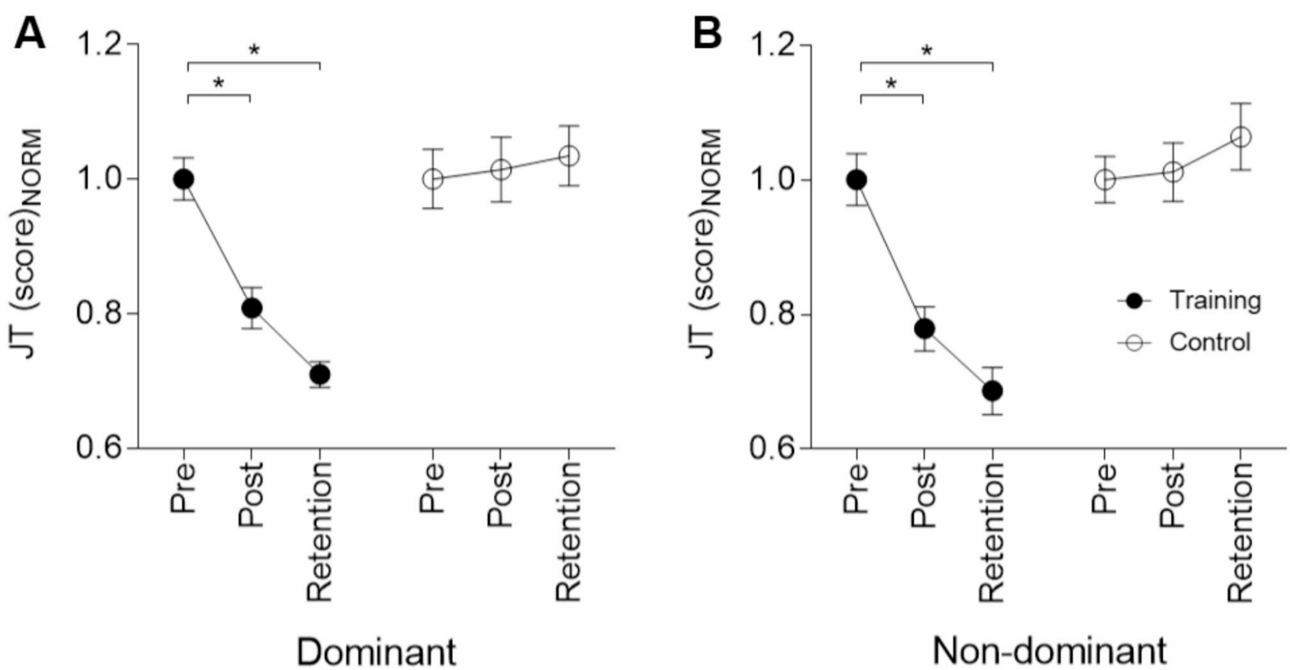

Fig. 3. The results of manual dexterity for the training and control group. (**A**) Jebsen Taylor Hand Function Test (JT) scores in the dominant hand during the pre-, post-, and retention-test. (**B**) JT scores in the non-dominant hand during the pre-, post-, and retention- test. The black dots represent the training group, and the empty dots represent the control group. All the JT results were represented as normalized data by calculating the values relative to the mean values obtained in the pre-test (JT $(score)_{NORM}$). *signifies significant ($p < 0.05$) differences in JT values among the tests.

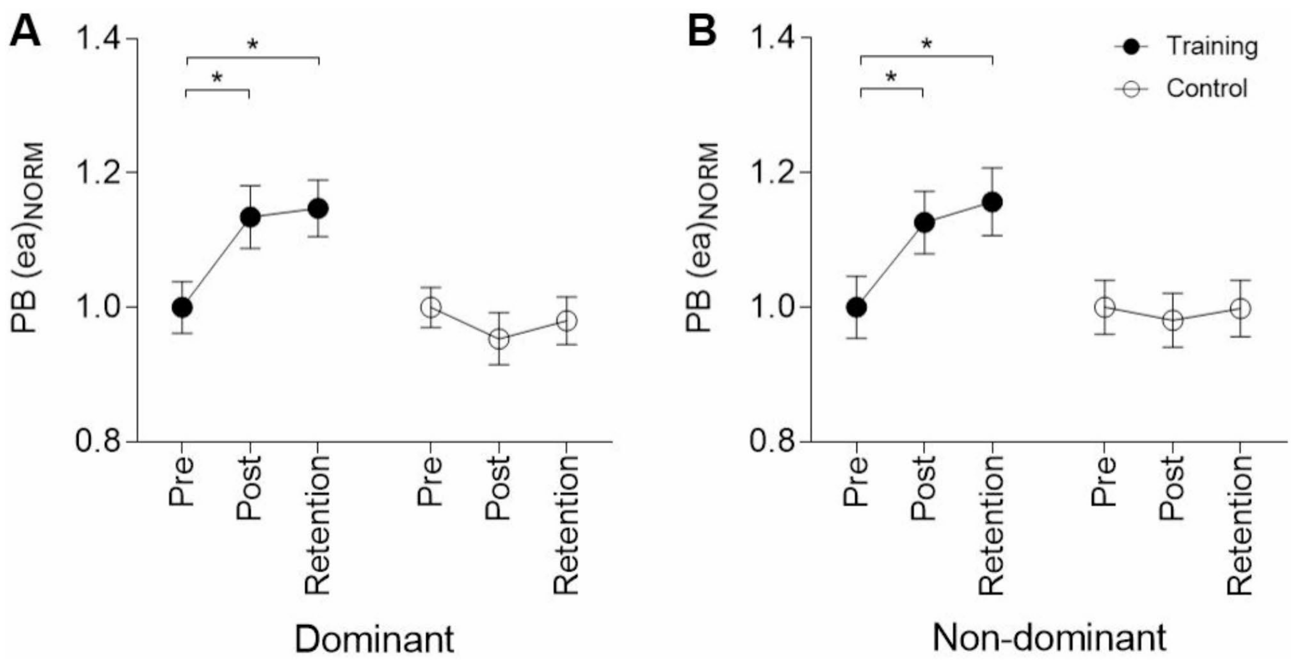

Fig. 4. The results of manual dexterity for the training and control group. (**A**) Peg Board test (PB) scores in the dominant hand during the pre-, post-, and retention- test. (**B**) PB scores in the non-dominant hand during the pre-, post-, and retention- test. The black dots represent the training group, and the empty dots represent the control group. All the JT results were represented as normalized data by calculating the values relative to the mean values obtained in the pre-test (PB $(ea)_{NORM}$). *Signifies significant ($p < 0.05$) differences in PB scores among the tests.

GROUP x TEST interaction [$F_{(1,23)} = 5.897$, $p = 0.005$, $\eta^2 = 0.204$]. Post-hoc comparisons indicated a significant increase in PB scores for the training group from the pre-test to the post-test ($p < 0.001$) and from the pre-test to the retention- test ($p < 0.001$), whereas no significant difference was observed between the post-test and the retention- test. In contrast, PB scores for the control group remained unchanged.

Discussion

In the current study, we aimed to investigate the impact of a novel hand training approach on hand strength and function in the elderly. To assess these effects, we measured both prehension strength and hand function using clinical tests, specifically PB and JT. Following the implementation of GBGT, we observed significant improvements in prehension strength and hand manual dexterity scores in both hands among all participants. These findings unequivocally demonstrate that our novel GBGT regimen induces CE effects in the elderly, in accordance with our initial hypothesis. Notably, the training's positive impact on dominant hand MGF extends to the contralateral limb, highlighting a robust transfer effect. Furthermore, the improvements in hand function, as assessed by the JT and PB, were also transferred to the untrained limb. This comprehensive set of results establishes that our novel unilateral limb training strategy enhances both prehension strength and motor function in the elderly, confirming the efficacy of GBGT in inducing CE effects.

Strength and dexterity improvements

Our findings reveal that participants in the training group, who completed the GBGT program, exhibited a substantial increase in MGF in both their dominant and non-dominant hands. This suggests that the GBGT program not only effectively enhances prehension strength but also contributes to the retention of this newfound strength. Notably, the observed increase in MGF in the non-dominant hand following training of the dominant hand underscores the potential for cross-activation and transfer of strength between limbs, supporting the concept of cross-education. This discovery carries significant implications, as it implies that interventions primarily targeting one limb can yield wide-ranging benefits. Furthermore, the enhancement in hand function, assessed through the JT and PB, in both the dominant and non-dominant hands further reinforces the efficacy of GBGT in enhancing manual dexterity.

Additionally, the concept of good manual dexterity, broadly defined as the skillful control of individual finger movements[20], holds paramount importance for various everyday hand and finger activities. However, previous studies have introduced the 'strength-dexterity trade-off hypothesis', which posits that an increase in muscular strength might result in diminished individual finger movement, subsequently leading to a reduction in dexterity[20,38]. In contrast, Shim et al.[19] proposed an alternative viewpoint suggesting that the reduction of force errors resulting from hand strength training could be considered an enhancement of the multi-finger motor system's ability to regulate finger strength, providing evidence that strength training may also yield improvements in hand dexterity.

As a consequence of our investigation, the training group exhibited noteworthy improvements in MGF, JT, and PB scores following five weeks of training. These outcomes provide compelling evidence that the novel hand training method not only enhances prehension strength but also significantly bolsters manual dexterity among the elderly. This finding challenges the traditional 'strength-dexterity trade-off hypothesis' and lends support to what we may term the 'strength-dexterity complementary relationship '. Multiple earlier studies have documented concurrent enhancements in force production and indices of force variability with strength training[39], and such results have also been observed in studies involving elderly individuals[15,40]. Therefore, the results of our study, in conjunction with existing evidence, collectively support the idea that strength and dexterity can be simultaneously improved. This revelation holds the potential to guide the development of new training methodologies not only for the elderly but also for the general population in the future.

Cross-education effects

The current study demonstrates that CE effects, typically studied in younger populations, are also evident in the elderly, as evidenced by significant improvements in both strength and dexterity in the trained and untrained limbs. CE refers to the phenomenon where unilateral training of one limb enhances performance in the contralateral untrained limb, driven by neural adaptations within the central nervous system[1,6]. Our findings suggest that the elderly, despite age-related declines in neural function, retain the capacity for CE effects, with observed improvements in both prehension strength and manual dexterity in both limbs following GBGT. These bilateral improvements may stem from neuroplastic changes, such as enhanced corticomotor excitability and reduced intracortical inhibition, which optimize motor performance across both hemispheres[6,41]. Techniques like transcranial magnetic stimulation have demonstrated such neural adaptations, including changes in cortical silent periods, short-interval intracortical inhibition, and intracortical facilitation, providing evidence of improved inter-limb coordination[42–44] .

In the elderly, CE effects may be amplified by compensatory mechanisms, as they often rely on distributed neural networks to maintain motor function[26,28]. Additionally, tasks requiring precise force control, such as GBGT, likely enhance sensory-motor integration, facilitating improved coordination and performance in both trained and untrained limbs. These findings suggest that CE is mediated by both corticospinal adaptations and shared sensory-motor pathways, enabling robust transfer effects even in the elderly[26]. While prior research has predominantly focused on CE's role in strength improvements[45,46], our study extends these findings to manual dexterity, with the simultaneous enhancement of both attributes challenging the traditional strength-dexterity trade-off hypothesis. By demonstrating that CE effects can effectively address age-related declines in motor function, this study highlights the potential for targeted interventions like GBGT to promote functional independence and quality of life in the elderly.

Our findings emphasize the effectiveness of a novel hand training program, designed to enhance both prehension strength and manual dexterity, while also facilitating the transfer of these improvements to the untrained limb in elderly individuals. While previous studies have primarily focused on CE effects in younger adults[5,6], our research marks a significant milestone by demonstrating that unilateral limb training extends its favorable outcomes to the contralateral limb in the elderly. This founding carries substantial significance, particularly considering that daily hand movements require the intricate coordination of both strength and individual finger control. These factors play a pivotal role in enhancing the overall quality of life, a crucial consideration for the elderly facing age-related physical declines.

One possible explanation for the robust transfer effect of both manual strength and dexterity in the elderly is the complexity of the task type. Our training program, involving the manipulation of a grip-type object using the hand, can be categorized as a complex task, requiring coordinated movements between the thumb and fingers. This task closely resembles real-life activities involving grasping and manipulating objects, which demand both coordination of individual fingers and the strength to hold objects. The complexity of our training program, mirroring daily hand functions, may account for the inter-hemisphere transfer effects observed in both prehension strength and dexterity[26]. Previous studies on CE effects in the elderly performing complex tasks have suggested that the mechanism of adaptive learning due to grip and lift tasks may similarly influence the neuro-circuitry of the hemisphere of the untrained limb[21].

Retention learning effects

The effect of training is also important to improve immediate performance, but it is also important to maintain acquired motor skills[47]. The results of the current study showed that the elderly' prehension strength increased by 18% after 5 weeks of training, and this gain was still evident at the 2-week retention test (21% above pre-test levels). The results of function tests also improved after 5 weeks, those improvements were maintained in the retention- test, indicating a sustained training effect on functional performance. Although the difference did not reach statistical significance after the 2-week detraining period, the data revealed a trend toward maintaining the observed improvements. These results indicate that the skill has stabilized, and confirming that gains persist for at least 2 weeks provides evidence of durable effects from the intervention[35]. Also, several studies reported retention effect of strength gains in the elderly at 5 and 6 weeks of detraining, respectively[48,49]. In dos Santos Mendes et al.[50], the effect of improving physical function through Wii Fit game training in the elderly was maintained even after the 60 days detraining period. The results of previous studies support our findings on the maintenance of training-induced strength and function increase in elderly. Elderly people have a high tendency to discontinue training due to unplanned factors such as disease, weather and environment[51]. Therefore, when constructing a training program for the elderly, it is also necessary to consider the retention effect of training effects. Consequentially, it is regarded that our novel hand training type and intensity are appropriate programs to maintain effect of training.

Finally, the results of the current study encourage further investigations of the CE effects on both manual strength and dexterity for functional independence of the elderly, which would provide ideas of evidence-based training for high-quality of life.

Limitations

One primary limitation of this study pertains to the specialized nature of the GBGT training, which primarily targeted finger grasping force control through isometric exercises. While the training was meticulously designed to improve particular aspects of prehension strength and dexterity by focusing on the manipulation of grip-type objects and controlling finger force, it may not fully address the broad spectrum of daily activities encountered by the elderly. This constraint is closely associated with the principle of training specificity, which suggests that training-induced adaptations are closely linked to the characteristics of the exercises performed. In this context, the study demonstrated improvements in both strength and dexterity, challenging the notion of strict training specificity. However, it remains a limitation that the training's effects may not entirely generalize to a wider array of functional activities, potentially restricting its real-world applicability.

Another notable limitation concerns the potential for participants to experience performance enhancements due to their increasing familiarity with the specific isometric finger grasping force control tasks used in the GBGT and the associated testing procedures. This familiarity may have contributed to improvements, and it's closely related to the principle of training specificity. To enhance research rigor and discern the authentic impact of the training, future studies should consider measures to control for potential learning effects related to the specific task and assessments used in isometric finger grasping force control. By doing so, researchers can mitigate the influence of both task specificity and test familiarity, contributing to a more comprehensive understanding of the training's effects on finger grasping force control and dexterity.

Data availability

Data sets generated during the current study are available from the corresponding author on reasonable request.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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