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Effect of moderate-intensity aquatic treadmill exercise on cognitive function and cerebral blood flow for healthy older adults

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ABSTRACT

To compare the effect of moderate-intensity aquatic treadmill exercise (ATM) on cerebral blood flow (CBF) and cognitive function in healthy older adults to that of moderate-intensity land-based treadmill exercise (LTM). This randomized controlled trial study was conducted between May 2023 and Oct 2023. Twenty-eight participants aged 60–80 were randomly assigned to either ATM group (N = 14) or LTM group (N = 14). Cognitive function and cerebral blood flow were assessed before and after the exercise. The outcome measures used in this study were the Digit Symbol Substitution Test (DSST) and the Digit Span Test (DST) to assess cognitive performance, and the mean middle cerebral artery blood velocity (MCAvmean) to evaluate CBF. A mixed effects model was used to analyze the within-group and between-group differences in cognitive function and CBF outcomes pre-to-post treadmill by SPSS. The DSST demonstrated a statistically significant improvement within both the ATM [β ± SE: −13.643 ± 2.407, 95 % CI: −18.749, −8.537] and LTM [β ± SE: −19.25 ± 3.66, 95 % CI: −26.424, −12.076] groups, indicating clinical significance in both groups. Both ATM and LTM groups exhibited post-exercise improvements within their respective groups for forward Digit Span Test (FDST) [ATM β ± SE: −0.143 ± 0.362, 95 % CI: −0.92, 0.634; LTM β ± SE: −0.286 ± 0.37, 95 % CI: −1.078, 0.506] and backward Digit Span Test (BDST) (ATM β ± SE: −1.741 ± 5.377, 95 % CI: −13.27, 9.792; LTM β ± SE: −6.729 ± 5.370, 95 % CI: −4.788, 18.24). In terms of $MCAv_{mean}$, there is a higher improvement of CBF in ATM group [β ± SE: −138.669 ± 67.9217, 95 % CI: −288.164, 10.826] than LTM group [β ± SE: −9.305 ± 70.076, 95 % CI: −153.617, 135.007]. Hence, a single bout of moderate-intensity ATM and LTM can enhance cognitive function and CBF in healthy older adults, suggesting their potential as preventive strategies against age-related declines.

1. Introduction

Aging poses a significant global health concern and places a considerable financial burden on society. Cognitive performance, including attention, memory, and executive function, tends to decline with age, with working memory being particularly affected (Ochsner and Kosslyn, 2013). In addition, cognitive decline is associated with a drop in health-related quality of life in elderlies (Kazazi et al., 2018). For instance, aging increases the risk of developing neurodegenerative diseases such as dementia, Alzheimer's disease, Huntington's disease. In a wider context, by 2050, the global economic burden of Alzheimer's disease and related disorders is projected to reach $16.9 trillion (Nandi et al., 2022). Therefore, it is imperative to investigate interventions aimed at delaying the age-related cognitive decline, thus preserving quality of life of older adults (Parra-Rizo et al., 2022).

As individuals age, there is a noticeable decline in cerebral blood flow (CBF). Resting CBF decreases by approximately 4 mL min^{-1} yr^{-1} after the age of 30 (Davenport et al., 2012). CBF is found to be diminished in several neurodegenerative diseases, such as mild cognitive disease, Alzheimer's disease and Huntington's disease (Renke et al., 2022). In individuals aged 71 years and older with Alzheimer's disease, a CBF value of 43 $cm·s^{-1}$ serves as a cut-off point (Xiao et al., 2022).

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Animal studies have revealed that impaired neuronal protein synthesis resulted from cerebral hypoperfusion contributes to learning and memory dysfunction in Alzheimer's disease (Zlokovic, 2011). Furthermore, it has been shown that there is a modest association between CBF and cognitive functioning, demonstrating that individuals with higher CBF having better performance on executive function (Leeuwis et al., 2018). Therefore, CBF can be considered to be a potential indicator of cognitive function. Thus, it is used in this study.

To evaluate the effect of cognitive function, Digit Symbol Substitution Test (DSST) and Digit Span Test (DST) could also be used, as they commonly assess specific executive function, which is a type of working memory. DSST evaluates a wide range of cognitive functions, including attention, visual search, and associative learning (Lezak, 2012). Moreover, DST encompasses forward DST (FDST) and backward DST (BDST) respectively accessing short-term memory and working memory (more specifically mental double-tracking) (Lezak, 2012; Yoshimura et al., 2023). Numerous studies have reported that there were more changes in working memory (Yoshimura et al., 2023) in BDST than FDST, with a higher activation of the left prefrontal cortex (Donolato et al., 2017). Table 1 lists the normative values of each cognitive test for healthy and mild cognitive older adults.

Regular exercise has been found to delay age-related cognitive deterioration, improve cognitive function and protect against cognitive disorders in healthy older adults (Colcombe et al., 2003). Colcombe et al. (Colcombe et al., 2003) reported morphological changes in the brain, an increase in grey matter of the frontal lobe in older adults who participated in a 6-month aerobic training. In the context of older adults' health, it is essential to maintain a good level of functional capacity, the absence of physical illnesses and psychological problems, as well as maintaining adequate levels of physical activity (Agustí et al., 2023). Moreover, more recent evidence has shown that a single bout of exercise could enhance cognitive function, specifically working memory in healthy older adults (O'Brien et al., 2017; McSween et al., 2019). O' Brien et al. revealed significant improvements in the forward digit span test (FDST) scores after one bout of 80-minute open skill ($p < 0.01$) and 70-minute closed skill exercise ($p < 0.05$), but no improvement in the sedentary group ($p = 0.94$) (O'Brien et al., 2017). This study aims to investigate the impact of a single bout of exercise on working memory performance.

Among different intensity levels, moderate intensity exercise demonstrates the most effective improvements to working memory in healthy older adults (Zhidong et al., 2021). Additionally, it is found that there is the maximal improvement of CBF when exercising at approximately 65 % maximal oxygen uptake (VO_{2max}) intensity, which is moderate intensity exercise (Parfitt et al., 2017). Thus, it may provide a potential explanation why working memory improves the most in moderate intensity exercise. To investigate the maximal effect of exercise on cognitive function, specifically working memory, this study adopts a single bout exercise intervention with moderate intensity.

Table 1
Norm and minimal clinically important difference for healthy elderly and individuals with neurocognitive disorder.

Variables	Subjects	Mean age	Norm	MCID
DSST correct count (Gignac et al., 2019; Ayán et al., 2017)	Healthy	63.57 ± 7.1	43.7 ± 1.37	−3.5 (Ayán et al., 2017)
	Mild AD	73.9 ± 6.0	19.5 ± 1.16	−3.8
FDST Maximum number of digits recalled (Cole and Becker, 2011)	Healthy	74	6	/
	Mild dementia	77	5	/
BDST Maximum number of digits recalled (Cole and Becker, 2011)	Healthy	74	4	/
	Mild dementia	77	3	/
$MCAv_{mean}$ (Renke et al., 2022)	Healthy	69.1 ± 5.6	46.1 ± 12.8 cm/s	/
	Alzheimer's disease	66 ± 13	43 ± 13 cm/s[a]	/

BDST, Backward Digit Span Test; DSST, Digit Symbol Substitution Test; FDST, Forward Digit Span Test; $MCAv_{mean}$, mean Middle Cerebral Artery Blood Flow velocity; MCID, Minimal Clinically Important Difference.

[a] Caution is required during analyzing. Data is derived from non-Asian population.

Compared to land-based exercise, aquatic exercise poses more benefits in improving CBF. Water immersion generates a hydrostatic pressure of 22.4 mmHg/ft., which induces peripheral vasoconstriction and rapid plastic deformation within individuals' body, centralizing blood distribution. For instance, neck-level water immersion raises right atrial blood pressure by 14–18 mmHg and increases cardiac output by 60 % (Cole and Becker, 2011). Carter et al. (Carter et al., 2014) demonstrated that water immersion is associated with increased mean arterial pressure and partial pressure of end-tidal carbon dioxide partial pressure, elevating cerebral blood velocities from 59 $cm \cdot s^{-1}$ to 64 $cm \cdot s^{-1}$ after 10 min in healthy young adults. Thus, aquatic exercise can improve CBF more than land-based exercise in healthy young adults (Pugh et al., 2015).

Previous studies have investigated the effect of different aquatic exercise, including deep-water running, shallow water running and swimming (Shoemaker et al., 2019). Compared to the above-mentioned exercises, Thus, our research will incorporate the utilization of ATM as a preferred method. To our current knowledge, there have been no studies examining the impact of ATM on working memory, and limited research has investigated its impact on CBF. Aquatic Treadmill Exercise (ATM) can be a practical and easily implemented option. It enables practitioners to easily monitor speed and cadence, thereby allowing greater control in maintaining the desired exercise intensity prescribed for patients. Additionally, owing to the provision of a handrail and a stable friction platform, it reduced likelihood of detrimental incidents, such as slips, falls, or related accidents inherent to activities like deep water running or swimming. Parfitt et al. (Parfitt et al., 2017) studied the effects of moderate-intensity incremental exercise on CBF. They assigned young adults into ATM and Land-based treadmill exercise (LTM) groups. They discovered that ATM augmented CBF velocity at various intensities than LTM ($p < 0.001$). Regarding the proposed mechanism between CBF and cognitive function, we hypothesize that ATM could increase both CBF and cognitive function more than LTM. However, to our current knowledge, no prior study has concurrently examined the impact of ATM impact on CBF and cognitive performance of healthy older adults.

This is the first study that aimed to fill in this research gap by concurrently comparing the effects of a single bout of moderate-intensity ATM on cognitive function and CBF in healthy older adults to that of LTM. Our objective of this study was to investigate (1) the effect of a single bout of moderate-intensity treadmill exercise (ATM and LTM) on cognitive performance and CBF, (2) whether a single bout of moderate-intensity ATM brings more improvement in the cognitive performance and CBF in healthy older adults than LTM. This study will provide clinical practitioners with a new alternative on how to delay cognitive deterioration and improve the cognitive performance of healthy older adults. Therefore, to address the study aims, we will test the following hypotheses. A single bout of moderate-intensity aerobic aquatic treadmill exercise (ATM) and land-based treadmill exercise (LTM) can both lead to improvements in cognitive function and cerebral blood flow (CBF) while a single bout of moderate-intensity aerobic aquatic treadmill exercise (ATM) can result in a greater improvement in cognitive function and cerebral blood flow (CBF) compared to moderate-intensity aerobic land-based treadmill exercise (LTM).

2. Methods

2.1. Participants

Our study, identified as HSEARS20230308007, received approval from the Human Subjects Ethics Committee of the Hong Kong Polytechnics University. A total of twenty-eight healthy older adults participants were recruited through convenience sampling in collaboration with community centers and by posting leaflets on the notice boards at The Hong Kong Polytechnic University (HKPolyU). In order to be included in the study, participants had to meet certain criteria, including being clinically healthy older adults individuals between the ages of 60 and 80, native Cantonese speakers who could read Chinese. Exclusion criteria encompassed musculoskeletal disorders that hindered running, as well as rheumatologic, cardiorespiratory, neurological, infectious, dermatological, psychiatric diseases, and contraindications to aquatic

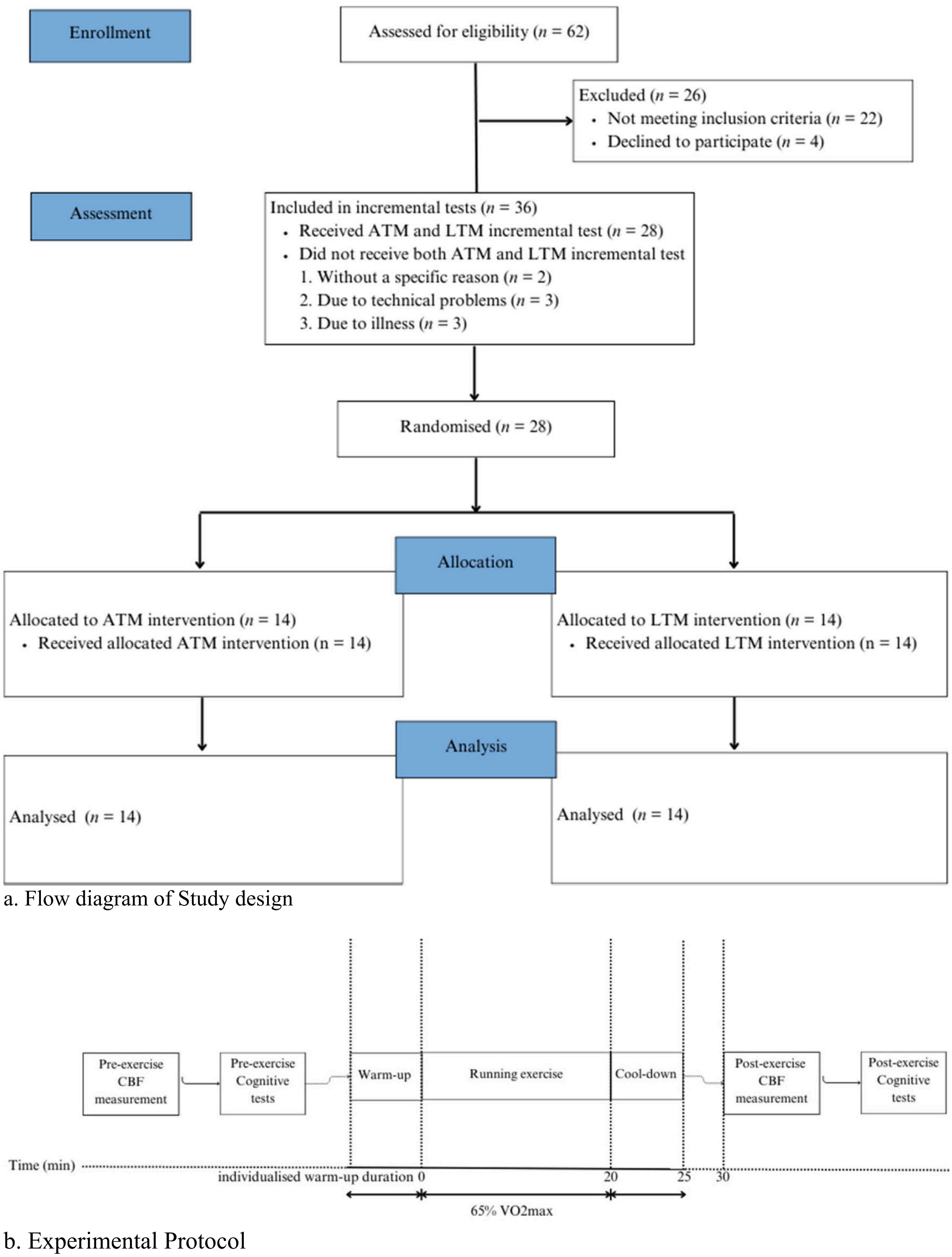


Fig. 1. Study design and experimental Protocol.
ATM, Aquatic Treadmill Exercise; CBF, Cerebral Blood Flow; LTM, Land-based Treadmill Exercise; n, number of subjects; VO_{2max}; maximum oxygen consumption.

exercises.

Prior to data collection, participants received comprehensive explanations regarding the research procedures, potential benefits, and associated risks involved in their participation. To ensure their voluntary involvement, participants were requested to complete an informed consent form. Additionally, they were required to fill out the Physical Activity Readiness Questionnaire to confirm their eligibility by declaring the absence of any exclusion criteria. Furthermore, the International Physical Activity Questionnaire (iPAQ) was administered to assess their physical activity levels for descriptive purposes.

To determine the appropriate sample size, the G*power software was utilized. It was determined that a total sample size of 24 or more subjectswould be adequate for detecting differences between groups, while accounting for an estimated 10 % attrition rate. This calculation was based on the effect size 0.8 (Hashitomi et al., 2023a), assuming a power of 0.8 at an alpha level of 0.05 (G*Power version 3.0.10).

2.2. Study design

A randomized controlled trial was conducted in this study. The 28 participants were randomly assigned to ATM and LTM group using an online random number generator (Randomizer). Each participant attended two incremental tests (both aquatic and land-based) and one session of exercise training (ATM or LTM). Fig. 1 provides a schematic diagram of the study design and ATM and LTM protocols. Participants were asked to refrain from any aerobic training for 48 h and caffeine for 24 h prior to the incremental test and exercise training.

2.3. Exercise treadmills and environment

A treadmill (Matrix T7xe Commercial Treadmill) at HKPolyU was used for land-based incremental test and exercise, and the ambient air temperature was maintained at 23 °C. A self-propelled aquatic treadmill at Whampoa Garden swimming pool (Hung Hom, Kowloon, HKSAR) was used for aquatic test and exercise, with water depth and temperature set at mid-chest level and 28 °C, respectively. According to the Aquatics Exercise Association (AEA), a comfortable water temperature for aquatic exercise is between 28.3 °C and 30 °C.

2.4. Aquatic and land incremental test

To improve accuracy, the incremental stress test was used to assess the VO_{2max} for determining participants' individualized speed of 65 % exercise intensity for the exercise training. Prior studies usually relied on standardized speeds which overlook the individual variations in physical fitness levels, resulting in different exercise intensities for different participants despite maintaining the same speed.

The Bruce protocol was followed for land incremental tests. For aquatic incremental tests, a protocol from Kanitz et al. (Kanitz et al., 2015) was followed, involving incremental increases in exercise loading starting from 85 beats per minute (bpm), with cadence increasing by 15 bpm every 2 min. The cadence was monitored using a metronome (IMT 300, Tokyo, Japan). During the incremental tests, participants' heart rate (HR) was monitored continuously and recorded at a frequency of 1 Hz using a HR sensor (Polar OH1, Kempele, Finland), which was shown to provide valid and reliable HR data (Bergamin et al., 2015). Additionally, gas exchange data were collected using the PNOE device (ENDO Medical, Palo Alto, California), a portable metabolic device that continuously measured volume and calculated expired gas concentrations on a breath-by-breath basis. PNOE was validated in earlier study (Tsekouras et al., 2019).

Prior to each session, the PNOE device was calibrated following the manufacturer's instructions. HR, oxygen consumption (VO_2), respiratory exchange ratio (RER), and rate of perceived exertion (RPE) per minute were recorded. The following are the criteria to terminate the test: (1) RER equal to or exceeding 1.20; (2) failure of heart rate elevation despite increasing intensity; (3) obvious indications of exhaustion (facial flushing, unsteady gait); and (4) refusal to continue despite encouragement. Data on VO_{2max}, HR, maximum heart rate (%HRmax) were collected for both ATM and LTM.

2.5. Exercise training

Exercise intensity at 65 % VO_{2max} was subsequently calculated. Participants performed an individualized incremental warm-up and 5-minute cool-down before and after exercise respectively. The individualized warm-up required the participants to follow the Bruce protocol (LTM) or Kanitz et al.'s protocol (ATM) (Kanitz et al., 2015) until they reached their stage of 65 % VO_{2max}. Both groups then performed running exercise for 20 min at 65 % VO_{2max}. In LTM, participants were asked to perform running exercise at the desired speed and inclination determined from the previous incremental tests. In ATM, participants were required to run in the desired cadence, which was monitored by a metronome. No external stimuli, such as verbal encouragement, was provided during exercise training. RPE and HR were measured continuously for safety and the monitoring of desired intensity.

2.6. Measurements

Cognitive function (measured by DSST and DST) and CBF (measured by mean middle cerebral artery blood velocity ($MCAv_{mean}$)) were evaluated both before and immediately after exercise training. For ATM, subjects were given 5 min to change their clothes before evaluation (Fig. 2).

2.6.1. Primary outcome – cognitive function (DSST & DST)

General cognitive performance and working memory were assessed before and after exercise by DSST and DST respectively. Both DSST and DST, with good reliability and validity in healthy older adults, were conducted using the Millisecond platform (Williamson et al., 2022; Gignac et al., 2019) to increase the inter-rater reliability. These tests were completed on an iPad (iPad Air 4) with a display placed 40 cm from the participants. The maximum number of correctly recalled digits and the total number of correct counts were recorded for DST and DSST respectively.

2.6.2. Secondary outcome – cerebral blood flow ($MCAv_{mean}$)

$MCAv_{mean}$ was recorded before and after the exercise training for 30 s with a transcranial Doppler system (Model EMS-9M, Shenzhen Delica Medical Equipment Co. Ltd, Shenzhen, Guangdong Province, China) in sitting position. An adjustable headband was used to attach the ultrasound probe over the temporal window to ensure a consistent insonation angle throughout the testing procedure. To ensure optimal image quality, ultrasound gel was applied between the probe and skin.

2.7. Data analysis and statistical approach

Statistical analysis was performed using IBM SPSS Version 25.0 (IBM Corporation, Armonk, NY) software with a significance level of 0.05 and 95 % confidence interval. Data was expressed as mean ± SD. Mean difference is calculated by taking the difference between the two means and dividing it by the standard error of the difference. First, an independent *t*-test, Mann-Whitney *U* test or chi-square test were used to ensure no significant differences among two groups in terms of all baseline variables. Independently *t*-test was used to analyze CBF, age, height, weight, BMI, physical level and LTM VO_{2max}, DSST correct count, FDST maximum number of digits recalled, BDST maximum number of digits recalled and MCAv mean. Mann-Whitney U test was used to analyze ATM VO2max. Chi-square test was used to analyze gender. A mixed effects model was used to analyze the within-group and between-group differences in cognitive function and CBF outcomes pre-to-post treadmill. β interactive effect estimates of mixed effect model,

Fig. 2. Environmental setups of measurements of cognitive function, cerebral blood flow and VO_{2max}.
ATM, Aquatic Treadmill Exercise; DST, Digit Span Test; DSST, Digit Symbol Substitution Test; LTM, Land-based Treadmill Exercise; $MCAv_{mean}$, mean Middle Cerebral Artery Blood Flow Velocity.

indicating the between-group difference after a single bout of moderate-intensity exercise. The model was comprised of the fixed effects of group (ATM vs LTM), time (pre vs post), and their interaction. Gender, age, body mass index, physical activity level, and VO_{2max} were included as covariates. Subjects with missing data were excluded from the SPSS analysis.

3. Results

3.1. Descriptive analysis of demographic information and baseline characteristics

Forty subjects were screened with baseline information collected. After dropouts (N = 12), twenty-eight subjects were recruited and randomized into ATM (N = 14) and LTM (N = 14) groups, with no dropouts afterwards. There were missing data in $MCAv_{mean}$ in ATM (N = 3) and

LTM (N = 2) groups due to poor transcranial Doppler velocity signals, because of poor temporal window for ultrasound transmission.

Baseline characteristics for the 28 subjects are included in Table 2. There was no statistically significant difference between ATM and LTM groups in the baseline characteristics ($P > 0.05$).

3.2. Effect of exercise on cognitive function

In DSST, the mixed effects model showed a statistically significant within-group improvement from pre- to post-exercise in ATM [$\beta \pm$ SE: -13.6 ± 2.4, 95 % CI: -18.7, -8.54] and LTM [$\beta \pm$ SE: -19.3 ± 3.66, 95 % CI: -26.4, -12.1] (see Table 3b). Both ATM (mean difference: -11.4 ± 6.76) and LTM (mean difference: -16.1 ± 7.88) demonstrated clinically meaningful improvements in DSST correct count, with reference to the published minimal clinically important difference (MCID) threshold of -3.5 for healthy older adults (Borland et al., 2022) (see Tables 1 and 3a). However, the interaction effect of group and trial in the mixed effects model was statistically insignificant for DSST [$\beta \pm$ SE: 3.27 ± 2.90, 95 % CI: -2.68, 902] (see Table 3c).

In FDST and BDST, there was a statistically insignificant improvement from pre-to-post exercise in either ATM or LTM group and statistically insignificant inter-group differences (see Tables 3b and 3c).

3.3. Effects of exercise on CBF

No statistically significant group-trial interaction effect was presented in $MCAv_{mean}$ [$\beta \pm$ SE: 0.37 ± 4.48, 95 %CI: -8.77, 9.52] (see Table 3c). There were statistically insignificant within-group improvements in $MCAv_{mean}$ in both ATM [$\beta \pm$ SE: -138.67 ± 67.9, 95 %CI: -288.16, 10.8] and LTM groups [$\beta \pm$ SE: -9.30 ± 70.07, 95 % CI: -153.62, 135.01] respectively (see Table 3b, Fig. 3).

Table 2
Baseline characteristics of ATM & LTM groups in terms of cognitive function and cerebral blood flow.

Variables	ATM (n = 14)	LTM (n = 14)	P-value
Age, yr[a]	65.9 ± 0.8	65.9 ± 1.0	0.955
BMI, kg·m^{-2a}	22.9 ± 0.8	22.9 ± 0.8	0.993
Gender, male %[c]	0.643	0.714	0.686
Physical activity level, MET-min per week[a]	3417 ± 701	3249 ± 629	0.860
VO_{2max} in aquatic condition, ml·min^{-1}·kg^{-1b}	29.7 ± 3.3	30.2 ± 3.4	0.769
VO_{2max} in land-based condition, ml·min^{-1}·kg^{-1a}	36.0 ± 2.4	35.5 ± 2.5	0.877
DSST correct count[a]	51.9 ± 13.3	48.7 ± 16.0	0.576
FDST Maximum number of digits recalled[a]	8.79 ± 1.72	8.57 ± 1.83	0.752
BDST Maximum number of digits recalled[a]	8.14 ± 2.96	8.14 ± 2.48	1.000
$MCAv_{mean}$, cm/s[a]	48.5 ± 8.1	45.9 ± 10.1	0.516

Data are presented in mean ± SD; Between group differences all statistically insignificant: $p > 0.05$; [a] is for continuous variables in normal distribution, examined by independent *t*-test; [b] is for continuous variables in abnormal distribution, examined by Mann-Whitney *U* test; [c] is for categorical variables, examined by chi-square test.
ATM, Aquatic Treadmill Exercise; BDST, Backward Digit Span Test; BMI, Body Mass Index; DSST, Digit Symbol Substitution Test; FDST, Forward Digit Span Test; LTM, Land-based Treadmill Exercise; n, number of subjects; $MCAv_{mean}$, mean Middle Cerebral Artery Blood Flow velocity; VO_{2max}, maximal oxygen consumption.

4. Discussion

This is the first study to simultaneously explore and compare the acute effect of moderate-intensity ATM and LTM on cognitive function and CBF in healthy older adults. Our findings reveal that DSST performance was significantly enhanced after either ATM or LTM exercise, while CBF and other cognitive function tests also showed improvement after exercise, although statistically insignificant. This suggests that a single bout of exercise can enhance certain aspects of cognitive function in healthy older adults with normal cognitive function.

4.1. General cognitive function (DSST)

Both ATM and LTM groups demonstrate clinically and statistically significant improvement in DSST. To the extent of our knowledge, no previous studies have investigated the acute effect of ATM on healthy older adults using DSST. A prior study compared the effects of six months combined treatment of water-based cognitive training (Brain Gym®) and aquatic aerobic exercise on cognitive function in healthy women using Symbol Digit Modalities Test (SDMT) (Ayán et al., 2017). Group A performed water-based cognitive training followed by fitness training and group B followed the same program in reverse order. The SDMT performance improvement of group A and B were 7.10 % and 4.45 % respectively. Our findings align with this study, showing that aquatic exercise can improve cognitive function, despite the absence of cognitive training. However, our study shows larger improvement in both ATM group (22.0 %) and LTM group (33.0 %). Several factors may account for this difference. Firstly, SDMT and DSST are slightly different although it shows similar clinical and psychometric properties. In SDMT, the placement of symbols and digits are reversed compared to DSST, making it relatively more challenging (Lezak, 1994). Yet, there is a strong correlation between the performance of SDMT and DSST. Second, our study recruited older participants (mean age of 65.9 ± 0.80 and 65.9 ± 0.98 in ATM and LTM groups respectively), compared to Ayan et al.'s (Ayán et al., 2017) study (mean age of 46.5 ± 12.3). A recent meta-analysis reveals that improvement in working memory performance is more pronounced in individuals aged over 65 (Rathore and Lom, 2017). The frontoparietal brain region, involved in executive function, is susceptible to the effects of aging. Thus, they may exhibit a heightened sensitivity to the impact of moderators like exercise (Audiffren and André, 2019). It is worth noting that we only assess the effect of a single bout ATM on DSST performance without cognitive training, suggesting that a single bout ATM alone can sufficiently boost non-specific cognitive function in a clinically meaningful way (Rathore and Lom, 2017).

LTM ($\triangle\beta = -19.25 \pm 3.66$) improves cognitive function in a larger extent than ATM (±SE: -13.643 ± 2.407) as shown by their mean differences. ATM group has a better baseline performance (mean: 51.857 ± 13.3) compared to LTM group (mean: 48.7 ± 15.9). Therefore, it may potentially limit room for ATM group to pose greater improvement compared to the LTM group. Regardless of the larger DSST improvement of LTM than ATM, our finding still aligns with previous research demonstrating the cognitive benefits of land-based exercise. Antunes et al. (Antunes et al., 2015) conducted a study on older adults individuals (mean age: 64.7 ± 3.56) and found that six months of land-based aerobic training resulted in significantly greater DSST improvement (8.92 %), compared to the non-exercise control group (0.9 %) ($p < 0.05$).

Although the mechanism of cognitive improvement is not studied in this study, it is worth noting that previous research has studied several mechanisms: the effect of enhanced CBF and BDNF, as mentioned in the introduction. A recent study reports that the improvement in BDNF level after exercise follows the trend of CBF improvement, suggesting the potential association between them (Walsh et al., 2020). Additionally, aquatic exercise is proven to increase BDNF level and cognitive function. Kang et al. suggested that 16-week regular aquatic exercise can enhance BDNF expression, thereby enhancing cognitive function in older adults

Table 3a
Within-group Mean difference in cognitive function and cerebral blood flow after 65 % VO_{2max} exercise in ATM and LTM group respectively.

Variables	ATM		Mean diff	LTM		Mean diff
	Pre	Post		Pre	Post	
DSST correct count	51.9 ± 13.3	63.3 ± 16.1	−11.4 ± 6.76	48.7 ± 16.0	64.8 ± 18.8	−16.1 ± 7.88
FDST Maximum number of digits recalled	8.78 ± 1.71	8.93 ± 1.54	−0.14 ± 1.41	8.57 ± 1.83	8.86 ± 1.61	−0.29 ± 1.44
BDST Maximum number of digits recalled	8.14 ± 1.96	8.71 ± 2.16	−0.57 ± 1.02	8.14 ± 2.48	8.36 ± 2.34	−0.21 ± 1.12
$MCAv_{Mean}$, $cm{\cdot}s^{-1}$	48.5 ± 8.10	51.0 ± 10.80	−2.56 ± 10.4	45.9 ± 10.1	47.3 ± 12.4	−1.35 ± 7.36

Data are presented in mean ± SD; Within-group mean difference is compared with post-exercise value, with a negative value indicates the improvement in each variable.
ATM, Aquatic Treadmill Exercise; BDST, Backward Digit Span Test; DSST, Digit Symbol Substitution Test; FDST, Forward Digit Span Test; LTM, Land-based Treadmill Exercise; $MCAv_{mean}$, mean Middle Cerebral Artery Blood Flow velocity.

Table 3b
Within-group changes of cognitive function and cerebral blood flow after moderate-intensity exercise in ATM and LTM group.

Variables	ATM (n = 14)	LTM (n = 14)
	△β ± SE (95 % CI)	△β ± SE (95 % CI)
DSST correct count	**−13.6 ± 2.41 (−18.7, −8.54)***	**−19.3 ± 3.66 (−26.4, −12.1)***
FDST Maximum number of digits recalled	−0.14 ± 0.36 (−0.92, 0.63)	−0.29 ± 0.37 (−1.08, 0.51)
BDST Maximum number of digits recalled	−1.74 ± 5.38 (−13.3, 9.79)	−6.73 ± 5.37 (−4.79, 18.2)
$MCAv_{mean}$, cm·sˆ−1	−138.7 ± 67.9 (−288.2, 10.8)	−9.31 ± 70.08 (−153.6, 135.0)

ATM, Aquatic Treadmill Exercise; BDST, Backward Digit Span Test; CI, confidence interval; DSST, Digit Symbol Substitution Test; FDST, Forward Digit Span Test; LTM, Land-based Treadmill Exercise; $MCAv_{mean}$, mean Middle Cerebral Artery Blood Flow velocity; n, number of subjects.
[*] Statistically significant differences within the same group with p<0.05 are presented in bold; Within-group difference is compared with post-exercise value, with a negative value indicates the improvement in each variable.

Table 3c
Inter-group differences in changes of cognitive function and cerebral blood flow from pre- to post-exercise between ATM and LTM groups.

Variables	Group[a]	Trial[b]	Differences, post vs pre, ATM vs LTM[c]
	β ± SE (95 % CI)	β ± SE (95 % CI)	β ± SE (95 % CI)
DSST correct count	−2.95 ± 5.21 (−13.6, 7.72)	−28.48 ± 35.932 (−102.1, 45.1)	3.27 ± 2.90 (−2.68, 902)
FDST maximum number of digits recalled	−12.7 ± 11.3 (−35.9, 10.5)	−0.28 ± 0.37 (−1.04, 0.47)	0.14 ± 0.52 (−0.93, 1.2)
BDST maximum number of digits recalled	−0.27 ± 0.60 (−1.50, 0.96)	−2.75 ± 4.06 (−5.53, 11.0)	0.17 ± 0.33 (−0.84, 0.51)
$MCAv_{mean}$, $cm{\cdot}s^{-1}$	−6.00 ± 8.75 (−23.7, 11.7)	−104.6 ± 76.6 (−26.1, 51.7)	0.38 ± 4.480 (−8.77, 9.52)

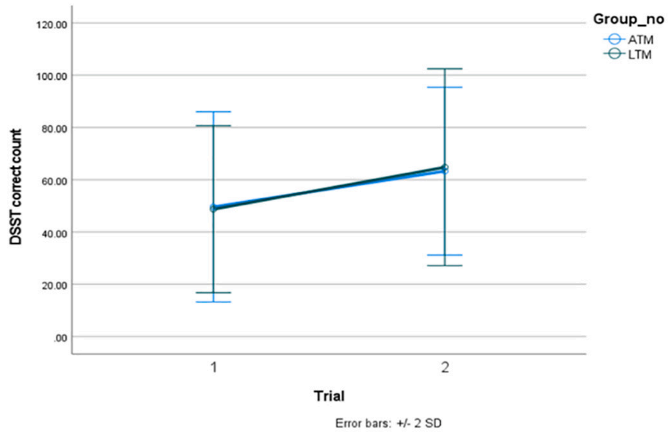
Significant differences at 0.05 level are presented in bold; [a]Reference category: LTM group. [b]Reference category: Post- exercise measurement. [c]β interactive effect estimates of mixed effect model, indicating the between-group difference after a single bout of moderate-intensity exercise; y = intercept + [ATM] + [Pre-exercise] + [ATM]*[Pre-exercise].
ATM, Aquatic Treadmill Exercise; BDST, Backward Digit Span Test; CI, confidence interval; DSST, Digit Symbol Substitution Test; FDST, Forward Digit Span Test; LTM, Land-based Treadmill Exercise; $MCAv_{mean}$, mean Middle Cerebral Artery Blood Flow velocity.

women, compared to non-exercise group (Kang et al., 2020). Limited research exists comparing the effects of land-based exercise and aquatic exercise on BDNF levels. However, we may conclude that ATM and LTM can improve cognitive functions, possibly due to the impact of BDNF.

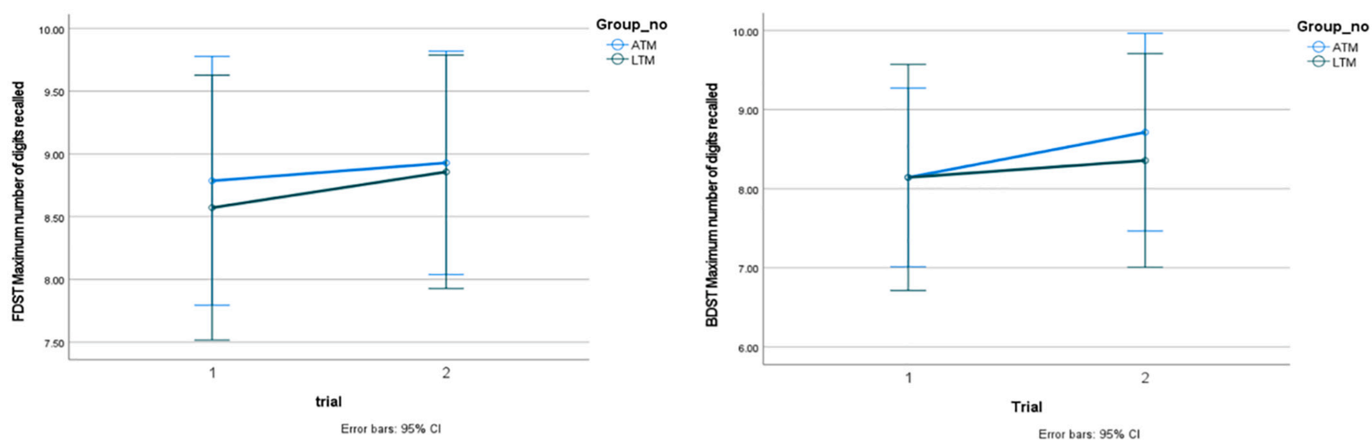
4.2. Working memory (DST)

Both LTM and ATM groups demonstrate improvement in DST, although this finding does not reach statistical significance. Specifically, our findings demonstrate improvements in FDST (ATM: 1.63 %, LTM: 3.34 %) and BDST (ATM: 7.01 %, LTM: 2.63 %). To our best of knowledge, the MCID of DST has not been established in the older adult population, no research investigates the effect of single bout of aquatic exercise on DST performance. However, there are two systematic reviews that illustrated the positive effect of single aerobic exercise on working memory in healthy older adults (McSween et al., 2019; Roig et al., 2013). Our finding aligns with them and further supports that moderate-intensity aquatic aerobic exercise can enhance working memory. The reason of not reaching statistical significance may be explained by the possibility of ceiling effect on the higher baseline performance compared to the norm in healthy older adults (FDST: 6, BDST: 4).

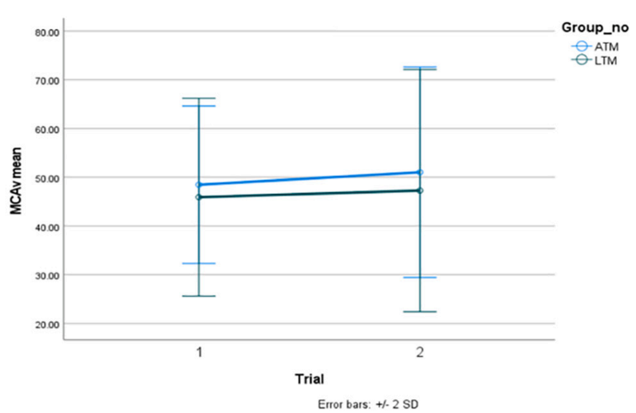
The result of FDST obtained contrasts with our hypothesis, while the result of BDST aligns with our hypothesis. Regarding FDST, LTM surprisingly boosts FDST performance more than ATM, which contrasts to our hypothesis. This may be due to the higher baseline performance of FDST in ATM (mean: 8.79 ± 1.72), compared to LTM group (mean: 8.57 ± 1.83). As ATM has a higher baseline than LTM, this may impose potential ceiling effect on the improvement of DST performance. Regarding BDST, ATM improves BDST performance more than LTM after exercise intervention, although this difference is statistically insignificant. One possible explanation for the higher improvement in working memory in single bout exercise of ATM than LTM is the higher activation of the prefrontal cortex (PFC). The study of Hashitomi et al. confirmed this hypothesis (Hashitomi et al., 2023b). They measured oxygenated hemoglobin (oxy-Hb) concentration, which indirectly measured CBF. The oxy-Hb levels were significantly higher (p = 0.039) in the channel covering left dorsolateral PFC in water cycling group than land cycling group, which implied that there may be a higher CBF to the left dorsolateral PFC. Thus, the improvement in working memory in aquatic exercises may be attributed to a higher CBF in dorsolateral PFC than land-based exercises. Our study aligns with these findings, supporting that ATM may activate left PFC more than LTM. It is evidenced by the greater improvement in BDST in ATM group than LTM group, since BDST is shown to have a higher activation of left PFC. Moreover, research supports that BDST detects working memory changes better



A. DSST correct count



B. DST maximum number of digits recalled



C. $MCAv_{mean}$

Fig. 3. The pre-post effect after intervention on cognitive function and cerebral blood flow.
ATM, Aquatic Treadmill Exercise; BDST, Backward Digit Span Test; DSST, Digit Symbol Substitution Test; FDST, Forward Digit Span Test; LTM, Land-based Treadmill Exercise; $MCAv_{mean}$, mean Middle Cerebral Artery Blood Flow Velocity. The 95 % Confidence Interval is illustrated in the figures. Fig. 3A. DSST correct count. Fig. 3B. DST results. Fig. 3C. $MCAv_{mean}$.

than FDST. BDST requires the use of mental double-tracking (i.e., holding a digit sequence in short-term memory and manipulating information in working memory by mentally reversing the order of the presented digits), while FDST predominantly tests the storage aspect of working memory (Lezak, 2012; Yoshimura et al., 2023). Thus, BDST might be more sensitive to age-related brain dysfunctions (Leung et al., 2011). This is an interesting finding that ATM can improve working memory more specifically mental-double tracking while LTM can improve the storage part of working memory.

Of note, the baseline performance in both groups exceeds the normal Chinese older adults normative data (Yoshimura et al., 2023), potentially due to the participant recruitment bias with high IPAQ scores and years of education. It has been previously established that strong correlations exist between MET-minutes and the Digit Span product score [$r^2 = 0.12$, $p = 0.01$] (O'Brien et al., 2017).

4.3. Cerebral blood flow ($MCAv_{mean}$)

There is an improvement trend of $MCAv_{mean}$ in both ATM and LTM groups, with ATM showing greater improvement than LTM despite the statistical insignificance. This result aligns with previous study reporting an increase in CBF after a single bout of aerobic exercise, with greater elevation in ATM group than LTM group (Parfitt et al., 2017). Our findings show an improvement (ATM: 5.28 %, LTM: 2.94 %) after exercise. In comparison with Parfitt et al. (ATM: 21 % and LTM: 12 %) (Parfitt et al., 2017), our results showed a smaller improvement in $MCAv_{mean}$. Several factors account for such disparity. First, it may be due to differences in subjects' characteristics. Parfitt's (Parfitt et al., 2017) study included young adults (27 ± 5 year) with a larger proportion of females (63 %) while our study recruited older adults (65.9 ± 0.9 year) with a smaller proportion of females (ATM: 35.7 %, LTM: 28.6 %). It is suggested that younger females experience greater CBF improvements induced by exercise, potentially attributed to hormonal factors, such as higher level of estrogen typically experienced throughout menstrual cycle (Smith et al., 2019). Second, our exercise protocols differ from the previous study. Parfitt's participants exercised at an incremental level of ATM or LTM (i.e., the treadmill speed increased every 2 min) until reaching the moderate intensity, which took a total of 14 min. Our participants ran for 20 min at a constant intensity. Ogoh et al. (Ogoh et al., 2014) discovered a general improvement in young athletes immediately after exercise with an attenuated improvement in $MCAv_{mean}$ at the 20-minute and 50-minute time points. This suggests that prolonged exercise may reduce the improvement in $MCAv_{mean}$, possibly due to hyperventilation, leading to a difference between our study and their study (Ogoh, 2017). The difference of CBF being statistically insignificant may be due to the small sample size, which will be explained more in the limitation.

Our result aligns with previous studies illustrating that a single bout of exercise can improve both CBF and cognition (Lucas et al., 2012a). Yet, this study cannot determine the causal relationship between CBF and cognition. Debate exists as cognitive gains may not be solely resulted from $MCAv_{mean}$ gain, which can possibly be explained by the complex cortical hemodynamics. While exercise elevates velocity, perfusion may not increase if the blood volume does not. Considering that CBF and cerebral perfusion may not have a direct causal relationship with cognitive function, others (Lucas et al., 2012b) have suggested that such improvement in cognitive function can be explained by the exercise-induced increase in regional cerebral metabolism, for instance, a greater oxygen extraction or due to the effect of temperature.

While a single bout of exercise may yield a statistically insignificant improvement in cognitive function or CBF, it should be recognized that chronic exercise may be able to impose a pronounced improvement on these outcomes. The proposed mechanism is that exercise improves cardiac output and hence CBF, which facilitates a rapid delivery of excitatory neurotransmitter (e.g., norepinephrine) to the prefrontal cortex, thus heightens cerebral metabolism and consequently improving cognitive performance (Olivo et al., 2021).

4.4. Strength & clinical implication

Several strengths of our study are identified. First, this RCT study investigated the effects of moderate-intensity exercise on $MCAv_{mean}$ and cognitive function in healthy older adults, an under-investigated population. Second, two validated cognitive tests are used to evaluate the cognitive function. Third, we conducted objective measurements of VO_{2max} to individualize participants' speed for 65 % VO_{2max} intensity, rather than relying on standardized speeds based on previous research. To mitigate the uncertainty of energy usage stemming from the varied cadence, an individualized cadence was adopted to ensure an accurate control of constant intensity.

Our study provides evidence to support the choice of exercise parameter for clinicians in the future. Since the positive effect of single-bout ATM and LTM running exercises is demonstrated through our findings, clinicians who are working with healthy older adults may consider the implementation of exercise with a moderate intensity for 20 min for cognitive preservation. To improve the quality of life for older adults, it is essential to promote regular participation in moderate-intensity exercises, such as ATM and LTM, which enhance cognitive function and cerebral blood flow.

4.5. Limitation

Our study has several limitations. First, during pre- and post-exercise assessments, the location of middle cerebral artery temporal window was challenging and time-consuming. Our research is prone to a lower success rate since old age is highly associated with insufficient temporal window (Lin et al., 2015). Second, our sample size is small due to various challenges during recruitment. The majority of participants were ineligible to proceed due to the absence of CBF signals. Several factors hinder the location of signal using transcranial Doppler ultrasonography, including temporal bone thickness, temporal window location, female gender, age and physical activity level (Chan et al., 2023).

4.6. Recommendation for future research

Future research can be conducted with a larger sample with increased exercise sessions, which can induce more neuroprotection against age-related cognitive decline. Research should also investigate the long-term cognitive and dose-response relationship. To gain a more holistic understanding of the impact of exercise on cognitive outcomes, potential covariates including age, gender, fitness and education level should be taken into consideration. Further research is necessary to investigate the causal relationship between the $MCAv_{mean}$ and cognitive performance.

5. Conclusions

This study provides preliminary evidence that a single bout of either ATM or LTM moderate-intensity exercise can improve cognitive function (specifically working memory) and CBF in community-dwelling healthy older adults. This confirms and extends upon previous research indicating that a single bout exercise boosts certain domains of cognitive function, not only in younger adults, but also for healthy older adults. Consequently, exercise may serve as a potential strategy preventing age-related declines.

CRediT authorship contribution statement

Billy, C.L. So: Writing – review & editing, Supervision, Conceptualization. **Hiko, C.Y. Cheung:** Data curation. **Y.P. Zheng:** Writing – review & editing, Investigation, Conceptualization. **Manny, M.Y. Kwok:** Writing – review & editing, Visualization, Validation, Supervision, Methodology. **Eugenie, Y.K. Man:** Writing – original draft, Project administration. **Fabiola, Tang Mok:** Writing – original draft, Project administration. **Gerald, C.N. Ng:** Writing – original draft, Project administration. **Nicco, N.L. Sze:** Writing – original draft, Project administration. **Stella, W.S. Tang:** Writing – original draft, Project administration. **Shamay, S.M. Ng:** Writing – review & editing, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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