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HIIT at Home: Enhancing Cardiorespiratory Fitness in Older Adults—A Randomized Controlled Trial

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ABSTRACT

Background: This study aimed to investigate the effectiveness of a 6-month home-based high-intensity interval training (HIIT) intervention to improve peak oxygen consumption ($\dot{V}O_2$peak) and lactate threshold (LT) in older adults.

Methods: Two hundred thirty-three healthy older adults (60–84 years; 54% females) were randomly assigned to either 6-month, thrice-weekly home-based HIIT (once-weekly circuit training and twice-weekly interval training) or a passive control group. Exercise sessions were monitored using a Polar watch and a logbook for objective and subjective data, respectively, and guided by a personal coach. The outcomes were assessed using a modified Balke protocol combining $\dot{V}O_2$peak and LT measures. General linear regression models assessed between-group differences in change and within-group changes for each outcome.

Results: There was a significant between-group difference in the pre-to-post change in $\dot{V}O_2$peak (difference: 1.8 [1.2; 2.3] mL/kg/min; exercise: +1.4 [1.0; 1.7] mL/kg/min [~5%]; control: −0.4 [−0.8; −0.0] mL/kg/min [approximately −1.5%]; effect size [ES]: 0.35). Compared with controls, the exercise group had lower blood lactate concentration (−0.7 [−0.9; −0.4] mmol/L, ES: 0.61), % of peak heart rate (−4.4 [−5.7; −3.0], ES: 0.64), and % of $\dot{V}O_2$peak (−4.5 [−6.1; −2.9], ES: 0.60) at the intensity corresponding to preintervention LT and achieved a higher treadmill stage (% incline) at LT (0.6 [0.3; 0.8]; ES: 0.47), following the intervention.

Conclusion: This study highlights the effectiveness of a home-based HIIT intervention as an accessible and equipment-minimal strategy to induce clinically meaningful improvements in cardiorespiratory fitness in older adults. Over 6 months, the exercise group showed larger improvements in all outcomes compared with the control group. Notably, the LT outcome exhibited a more pronounced magnitude of change than $\dot{V}O_2$peak.

1 | Introduction

Regular physical exercise has been shown to attenuate age-related physiological decline, reduce disease risk, and improve quality of life [1, 2]. However, a significant proportion of older adults fail to meet the minimum World Health Organization recommended levels of physical activity [3] (150 min of moderate or 75 min of vigorous weekly exercise [4]), potentially exacerbating health-related challenges associated with an aging population [5]. Notably, cardiorespiratory fitness surpasses well-established risk factors such as obesity, smoking, and high blood pressure in predicting premature mortality [6, 7]. Consequently, offering effective and evidence-based exercise programs tailored to improve cardiorespiratory fitness could positively influence the ever-growing aging population [8].

Peak oxygen consumption ($\dot{V}O_2$peak) (i.e., the highest rate of oxygen uptake measured during a single "maximum" test) is considered valid and reliable to determine cardiorespiratory fitness in exercise training research [9], and it is shown that a lower $\dot{V}O_2$peak notably increases the odds of dependence in older adults by 14% for each mL/kg/min reduction [10]. Despite this, it is evident that the physical activity patterns of older adults are primarily at low to moderate intensity [11], and most daily activities (e.g., walking/stairs/gardening) can be efficiently performed with a $\dot{V}O_2$peak as low as 18 mL/kg/min [12]. Furthermore, $\dot{V}O_2$peak has a significant genetic component, contributing to the prevalence of low responders to exercise training programs [13]. The existence of individual response patterns has shown that low (or non)-responders in $\dot{V}O_2$peak can still show improvements in other endurance-related variables, such as lactate threshold (LT) (i.e., the intensity of exercise in which the accumulation rate is faster than the removal rate of blood lactate concentration ($[La^-]_b$)) [14]. Along these lines, classifying individuals as nonresponders based on a single parameter overlooks the range of possible biological exercise adaptations [15]. Therefore, alongside $\dot{V}O_2$peak, it is important to consider other metrics when assessing changes in cardiorespiratory fitness, such as exercise economy and LT, which may offer a more comprehensive assessment of fitness levels that accommodates diverse individual responses and is meaningful for older adults' daily lives.

Recent public health promotions have highlighted interval training as an alternative exercise strategy, with high-intensity interval training (HIIT) gaining prominence [16]. HIIT involves short bouts of intense exercise (i.e., >80% of maximal heart rate) interspersed by periods of recovery. Originally developed to enhance athletic performance, HIIT saw a pivotal shift a decade ago, with new studies initiating a broad, unified, and expanding body of evidence highlighting HIIT's benefits across numerous health outcomes [17]. Furthermore, compared with moderate-intensity continuous training (MICT), HIIT is potentially better suited to busy schedules due to its time-efficiency and may elicit similar or superior improvements in the cardiorespiratory fitness of older adults [18].

Moreover, while numerous exercise interventions have been conducted under controlled laboratory conditions [19], the dynamics of older adults' exercise engagement beyond controlled environments remain less explored [19, 20]. Additionally, studies evaluating health outcomes commonly report limited information on adherence to intended exercise interventions, typically focusing on attendance (e.g., the ratio of attended to planned exercise intervention) and rates of lost to follow-up (e.g., number completing post-intervention test sessions) [21, 22]. Therefore, there is a need for more extensive and extended studies under free-living conditions to investigate whether HIIT is feasible as a public health strategy among older adults [19]. The "Generation 100" randomized control trial (RCT) has already demonstrated that older adults can perform HIIT without strict supervision (i.e., offered supervised sessions every 6 weeks and optional outdoor sessions with exercise physiologists), indicating that home-based HIIT requiring minimal equipment can effectively enhance older adults' cardiorespiratory fitness [23]. However, conclusions around true adherence are limited as this primarily relied on self-reported data, which is susceptible to recall bias [24]. Furthermore, cross-country population differences, including varying levels of education and physical activity, as highlighted by differences between the United Kingdom (UK) and Norway in the study by Loyen et al. [25], may impact the implementation of exercise protocols in real-world settings. Thus, the present study aimed to extend previous literature by collecting objective adherence data in the context of home-based HIIT among both UK and Norwegian populations.

In summary, HIIT is known to be a reliable method to improve cardiorespiratory fitness in the general and older adult population [16, 18]. Performing HIIT in a real-world home-based exercise setting presents a potentially practical and time-efficient exercise modality that, with commitment and adaptation, could be integrated into older adults' daily routines. However, current knowledge is lacking regarding objective adherence in real-world home-based intervention settings and the efficacy of these types of interventions to attenuate age-related decline in cardiorespiratory fitness, assessed using either $\dot{V}O_2$peak or LT. Therefore, the overall aim of the present study was to investigate the effectiveness of a 6-month home-based HIIT intervention to improve $\dot{V}O_2$peak and LT in older adults.

2 | Materials and Methods

2.1 | Study Design

The present study was part of the "Fitness, Ageing, and Bilingualism" (FAB) project. See Open Science Framework (OSF) preregistration (osf.io/6fqg7) or project website (fab-study.com) for more detailed information. Interested participants were screened for study inclusion based on online questionnaires (Physical Activity and Health Pre-screening Questionnaire, Language Experience and Proficiency Questionnaire), and eligible participants were randomly assigned to either a home-based exercise group or a passive control group stratified by age and sex using a bespoke algorithm (Figure 1). However, if participants had a partner (whom they lived with) also taking part in the study, they would be assigned to the same group. Participants had no prior knowledge of their group assignment before enrollment to mitigate any potential biases associated with their intention or motivation to participate in the exercise program. The same standardized testing protocol was performed pre- and post-intervention (26 weeks). The exercise group followed a standardized exercise program with required individual adjustments (three sessions per week), while the passive control group were asked to maintain their normal physical activity level. The first 4 weeks of the exercise intervention were termed the "familiarization period," where exercise intensity and duration were lower, allowing participants to understand the training protocol and ensure proper execution technique. The exercise group received detailed written and video instructions and was guided by a training coach throughout the intervention via monthly emails, phone calls, and face-to-face meetings. The desired training intensity was >80% of peak heart rate (HRpeak), using the highest recorded measure from the incremental treadmill $\dot{V}O_2$peak test.

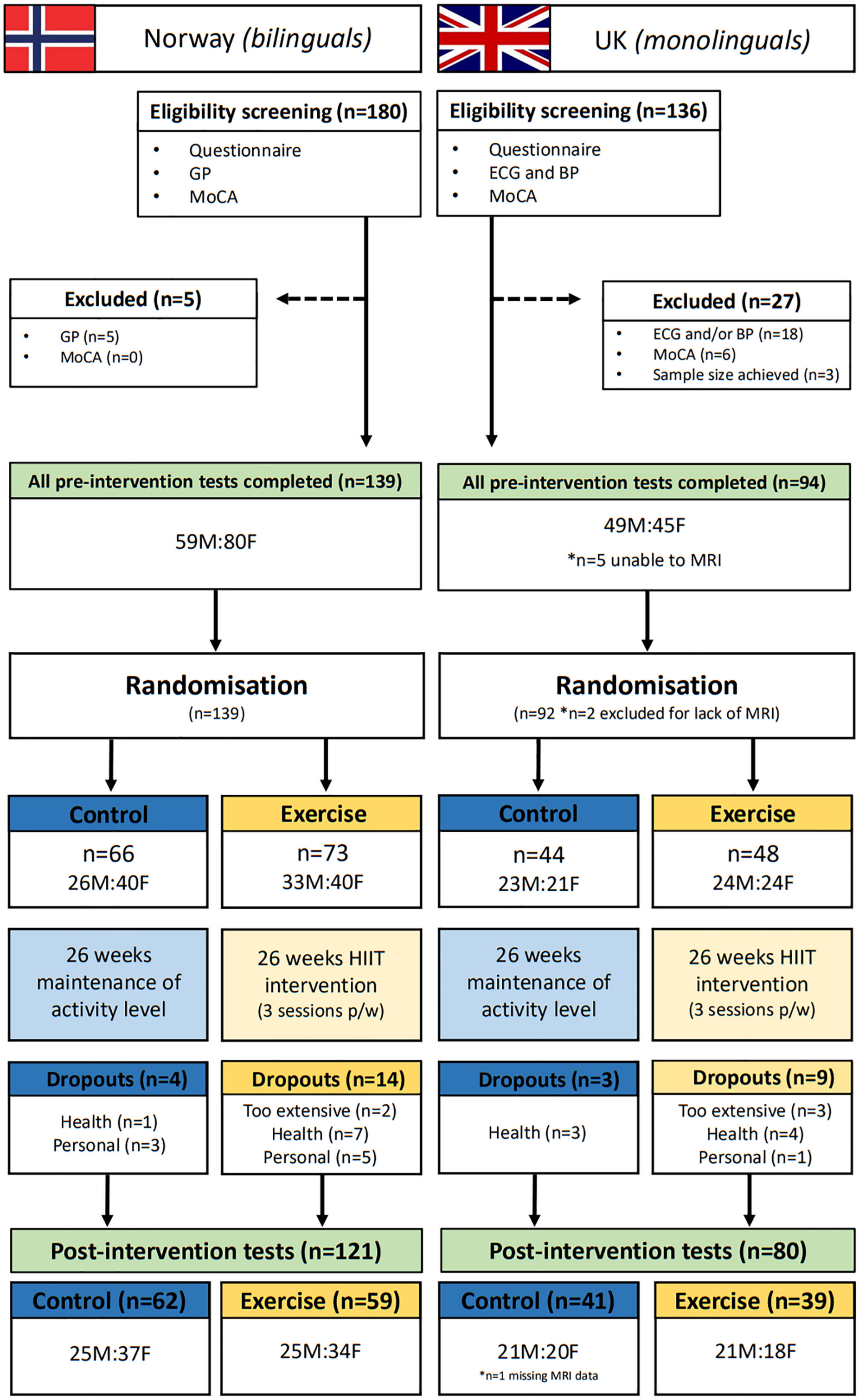

FIGURE 1 | Study design flowchart illustrating the timeline for screening, testing, randomization, intervention, participant dropouts, and total amount of participants completing the whole intervention. BP, blood pressure; ECG, electrocardiogram; F, female; GP, general practitioner; HIIT, high-intensity interval training; M, male; MoCA, Montreal cognitive assessment; MRI, magnetic resonance imaging; *n*, number; p/w, per week.

2.2 | Participants

A total of 233 (age 67 ± 6 years; body mass 80 ± 14 kg; BMI 27 ± 4 kg/m^2) participants were recruited from the south of Norway ($n = 139$) and the West Midlands region in the UK ($n = 94$). Participants, comprising healthy home-dwelling males and females (125 F:108 M) aged between 60 and 84 years, were non-smokers for at least 5 years, had normal or corrected-to-normal vision and hearing, no diagnosed language impairments (e.g., dyslexia or stuttering), and no illness or disease that would prevent safe participation in HIIT (e.g., cardiovascular, metabolic, respiratory, neurological, kidney, liver, or cancerous disease). Additionally, participants self-reported not meeting the recommended global physical activity guidelines (i.e., completing <150 min of moderate-intensity exercise per week). In Norway, each participant had a written health certificate from their general practitioner to participate, and in the UK, participants with severe electrocardiogram abnormalities (e.g., ST depression, long QT, heart block, wide QRS) or high blood pressure (systolic/diastolic blood pressure of >160/>90 mmHg, respectively) were excluded. These criteria were designed to recruit generally healthy but physically inactive older adults to maintain consistency and reliability across the wide range of assessments included in our project. The variation in screening methods between our study's Norwegian and UK branches was necessitated by the distinct requirements for ethical approvals in each country, reflecting our adherence to local regulatory and ethical standards.

2.3 | Ethics Statement

The study was performed in accordance with the Declaration of Helsinki, and data was stored according to the Norwegian Agency for Shared Services in Education and Research (ref.: 239577). The project was approved by the Regional Committee for Medical and Healthcare Research Ethics in Norway (REK, ref.: 163931) and received institutional ethical approval (University of Agder: The Ethical Board at the Faculty of Health and Sport Science; University of Birmingham: ERN 20_1107).

Prior to participation, all participants received a study information sheet describing the project structure and the inclusion criteria. The study description also informed participants of their rights regarding participation and withdrawal, as well as the data confidentiality procedures. Having read the description, those willing to participate signed an informed consent form.

2.4 | Exercise Intervention

A comprehensive description of the exercise intervention is available in the Supporting Information. The intervention included three weekly sessions (one circuit and two interval training sessions) designed for home or outdoor execution, necessitating either no or low-cost equipment (Table 1).

The initial 4 weeks served as a familiarization period, introducing participants to the training program and equipment, including the Polar Unite watch, Polar H9 chest sensor (Polar Electro Oy, Kempele, Finland), and a training logbook. Prerecorded exercise videos were available for technique familiarization. The Polar watch, preprogrammed to display real-time % of HRpeak during sessions, facilitated objective monitoring of exercise FITT factors (frequency, intensity, time, and type), while the training logbook provided subjective monitoring (i.e., ratings of perceived exertion). Personal exercise coaches (SHF, JF) guided participants, with weekly follow-ups during the familiarization period and monthly thereafter. These follow-ups ensured participants' proficiency with the training program/equipment and promoted motivation.

Each HIIT session lasted 40–60 min, incorporating a warm-up, main exercise phase, and cool-down. Circuit training involved six exercises with three sets lasting 45 s, performed at >80% of HRpeak, with 30 s rest between sets and 90 s between exercises. Interval training, primarily uphill walking, was performed with 2-min exercise intervals interspersed with 2-min active recovery periods. The number of intervals gradually increased throughout the program (Table 1). The linear periodization was chosen to ensure a gradual increase in high-intensity work, starting with a low volume to facilitate safe adaptation and accommodate the home-based nature of the program, thereby enhancing participant adherence and simplifying self-administration. Alternative equipment, like rowing machines or exercise bikes, were occasionally allowed to adjust to individual preferences and circumstances (i.e., due to minor muscle or joint-related issues). Physical activity levels of both exercise and control groups were assessed thrice during the intervention (start, mid-point, and end) using an ActiGraph GT3X+ (ActiGraph Corp., Florida, USA) monitor worn over 7-day periods.

2.5 | Measurements

A detailed description of all measurements, including cardiorespiratory fitness, adherence, and physical activity level, can be found in the Supporting Information. The primary outcome was $\dot{V}O_2$peak, and the secondary outcome was LT.

2.5.1 | Cardiorespiratory Fitness

$\dot{V}O_2$peak and LT were measured using a combined modified Balke treadmill protocol [26]. Respiratory gases (oxygen consumption [$\dot{V}O_2$] and carbon dioxide production) were recorded continuously using a facemask (Hans Rudolph, Kansas, USA) and a Vyntus CPX metabolic cart (Vyaire, Mettawa, Illinois, USA) and finger-pick $[La^-]_b$ was analyzed with an EKF Biosen lactate analyzer (EKF Diagnostics, Cardiff, UK). Participants started with self-paced walking, transitioning to a standardized progressive walking protocol until reaching volitional exhaustion. The protocol began at 3.8 km/h with a 4% incline, incrementally increasing the gradient by 3% every 4 min until a $[La^-]_b$ of 2.1 mmol/L above baseline, which determined the LT [27]. Key metrics, including $[La^-]_b$, $\dot{V}O_2$, heart rate (HR), and ratings of perceived exertion (Borg's scale 6–20 [28]), were recorded at the end of each 4-min stage and post-test. After determining the LT, exercise intensity was increased each minute via increased gradient (2% increments up to a maximum incline of 20%) or speed (0.5 km/h increments) until participants reached volitional exhaustion. In Norway, gradient was increased first up until 20%, with speed increased thereafter if necessary; in the UK, gradient at LT was maintained with speed increased until volitional exhaustion. This variation was due to slight differences in protocol interpretation between the two sites. HR was consistently monitored using a Polar H9 sensor in Norway and a 12-lead electrocardiogram (Cardiosoft, Vyaire, USA) in the UK, with the highest recorded HR representing HRpeak. Borg's scale provided an estimation of participants' perceived exertion, and $\dot{V}O_2$peak was defined as the mean of the two highest 30-s recordings. The sub-maximal test necessitated completing at least three treadmill stages before reaching the LT.

TABLE 1 | Training program overview.

	High-intensity interval training						High-intensity circuit training						
Mesocycle	**Sessions/ Week**	**Bouts/ Session**	**Work duration (min)**	**Rest duration (min)**	**Session intensity (%HRpeak)**	**Total duration (min)**	**Sessions/ Week**	**Main exercises (*n*)**	**Repetitions/ Sets**	**Work duration (s)**	**Rest duration bs/be (s)**	**Session intensity (%HRpeak)**	**Total duration (min)**
Familiarization (Weeks 1–4)	2	1	20	n/a	57–70	20	1	6	12 × 1	n/a	n/a	57–70	10
	2	1	20	n/a	57–70	20	1	6	12 × 2	n/a	60/90	57–70	20
	2	5	2	2	64–76	18	1	6	12 × 3	n/a	60/90	64–76	25
	2	5	2	2	>80	18	1	6	n/a × 2	45	60/90	64–76	25
Mesocycle 1 (Weeks 5–7)	2	5	2	2	>80	18	1	6	n/a × 3	45	30/90	>80	30
Mesocycle 2 (Weeks 8–11)	2	6	2	2	>80	22	1	6	n/a × 3	45	30/90	>80	30
Mesocycle 3 (Weeks 12–15)	2	7	2	2	>80	26	1	6	n/a × 3	45	30/90	>80	30
Mesocycle 4 (Weeks 16–19)	2	8	2	2	>80	30	1	6	n/a × 3	45	30/90	>80	30
Mesocycle 5 (Weeks 20–23)	2	9	2	2	>80	34	1	6	n/a × 3	45	30/90	>80	30
Mesocycle 6 (Weeks 24–26)	2	10	2	2	>80	38	1	6	n/a × 3	45	30/90	>80	30

Note: Main exercises: air squats, high knee lifts, step-ups, push-ups, reverse lunges, mountain climbers. Total duration: main session independent of warm-up and cool-down.
Abbreviations: bs/be, between sets/between exercises; HRpeak, peak heart rate; *n*, number; n/a, not applicable.

2.5.2 | Training Adherence

Adherence was calculated using only postfamiliarization main session data (i.e., Weeks 5–26, excluding warm-up and cool-down), and all HR data were visually inspected to quality-check for measurement errors. Sessions were categorized as interval, circuit, or alternative, with the latter referring to non-prescribed activities like rowing, hiking, or any type of continuous exercise. Adherence calculation and reporting employed a novel method using metabolic equivalents (METs) [22]. Prescribed cumulative MET-minutes (MET-min) for the intervention period were calculated by summating the planned MET-min from each session. Planned MET-min/session were estimated by multiplying the planned session duration by the MET code corresponding to 70%–76% of HRpeak as per the American College of Sports Medicine guidelines [29]. Mean HR for each session (including recovery bouts) was estimated to fall within this range. This method was applied to all participant sessions, considering the actual session duration and mean % of HRpeak. For each metric, adherence was calculated as the percentage achieved relative to what was prescribed.

2.5.3 | Physical Activity Level

The ActiGraph GT3X+ (ActiGraph Corp., Florida, USA) was used to assess the participants' (exercise and control group) physical activity level during three distinct 7-day periods at the beginning, mid-point, and end of the study. The participants received a preprogrammed accelerometer physically or by mail, including standardized instructions on how to wear the device. The physical activity levels evaluated by the accelerometer are presented as the number of minutes spent in intensity-specific categories per day (section 1.3 in the Supporting Information).

2.6 | Statistical Analysis

The original sample size calculation for the FAB study can be found in the OSF preregistration (osf.io/6fqg7). Additional calculations were performed in the G*Power version 3.1 software for the primary outcome in the present paper. Based on previous studies, investigating the effectiveness of aerobic training programs in older adults [8, 18, 30] and with an estimated dropout rate of 15%, we needed ≥25 participants in each group to detect a 10 ± 9% between-group difference in $\dot{V}O_2$peak, with 80% power and an α-level at 5%.

Statistical analyses were performed using IBM SPSS Statistics 29 for Windows (IBM Corp., Armonk, NY, USA), while figures were generated in Prism 8.0.1 (GraphPad Software, San Diego, CA, USA). In adherence to the intention-to-treat principle, all available participant data were analyzed based on their original group allocation. The MCAR test (missing completely at random) by little was used to assess missing data patterns. In addition, participant characteristics of dropouts to those completing the intervention were compared with independent-sample *t*-tests. Missing posttest values were addressed through multiple imputation with pretest and change score variables as predictors [31]. One participant only performed the $\dot{V}O_2$peak test due to trypanophobia, while 18 participants only performed the submaximal LT test due to minor electrocardiogram abnormalities. 15 submaximal LT tests did not meet the criteria of completing ≥3 treadmill stages before reaching LT, while eight were excluded due to measurement errors. For the secondary outcome, posttest values of $[La^-]_b$, HR, and $\dot{V}O_2$ corresponding to the pretest LT stage were compared; note that only participants who reached the same or higher LT stage at the posttest could be included in this analysis (i.e., excluding 21 participants [n = 15C:6E]).

General linear regression models (GLM) assessed between-group differences in change and within-group changes for each outcome. The models incorporated group, time (pre and post), and a group × time interaction, including age, sex, and country of residence as covariates. Results are presented as GLM-estimated mean changes, with 95% confidence intervals (CI). Effect sizes (ES) were calculated using pre- and postintervention means, standard deviations (SD), sample size, and pre–post correlations for both the exercise and control groups. In interpreting the ES's, we adhered to Cohen's convention; where an ES of 0.2 was considered small, 0.5 was considered moderate, and 0.8 was considered large [32].

Three different sensitivity analyses were conducted on all outcomes: original dataset, per-protocol, and age-adjusted $\dot{V}O_2$max criteria. The original dataset analysis excluded dropouts, the per-protocol analysis excluded exercise group participants with <80% mean overall adherence, and the age-adjusted $\dot{V}O_2$max criteria excluded those not meeting either a $[La^-]_b$ of ≥4.0 mmol/L or an RER of ≥1.0 [33] during both pre- and posttests.

3 | Results

3.1 | Study Participants

The main characteristics of the participants at baseline are shown in Table 2. There were no significant differences in any of the characteristics between the exercise and control group at baseline (p > 0.05). For detailed information regarding pre- to postchanges in participant characteristics along with end criteria measurements for the $\dot{V}O_2$peak test, see Table S1.

3.2 | Changes in Cardiorespiratory Fitness Pre- to Post-Intervention

From pre- to postintervention, the exercise group showed an increase in $\dot{V}O_2$peak compared with the control group, with a between-group difference of 1.8 [1.2; 2.3] mL/kg/min (ES: 0.35) and 0.10 [0.06; 0.15] L/min (ES: 0.20), for relative and absolute $\dot{V}O_2$peak, respectively. See Table 3 for a detailed overview of results and Figure 2 for grouped distributions and individual variations in $\dot{V}O_2$peak changes.

The exercise group completed a greater number of treadmill stages (TMS) preceding LT compared with the control group, with a mean between-group difference of 0.6 [0.3; 0.8] (ES: 0.47). The % of HRpeak at the preintervention LT (LT-pre) decreased

TABLE 2 | Participants' baseline characteristics.

Variables	Exercise Mean ± SD	Control Mean ± SD
n	122 (64 F:58 M)	111 (61 F:50 M)
Age (years)	67.6 ± 5.9	67.0 ± 5.2
BMI (kg/m^2)	27.2 ± 3.5	27.4 ± 4.1
Body mass (kg)	80.2 ± 13.5	80.0 ± 14.8
$\dot{V}O_2$peak (mL/kg/min)	27.7 ± 3.6	27.9 ± 4.8
$\dot{V}O_2$peak (L/min)	2.22 ± 0.55	2.24 ± 0.58
Physical activity level (*n*)	115	106
Sedentary (min/day)	658 ± 71	650 ± 69
LPA (min/day)	167 ± 42	170 ± 42
MPA (min/day)	42 ± 24	41 ± 22
VPA (min/day)	1.1 ± 2.8	1.1 ± 2.6
>150 min MVPA/week (*n*)	94 (82%)	83 (78%)
Education level		
Compulsory (%)	14	16
Higher (%)	27	20
Undergraduate (%)	29	36
Postgraduate (%)	30	28

Note: Values are presented as mean ± SD.
Abbreviations: BMI, body mass index; F, female; LPA, low-intensity physical activity; M, male; MPA, moderate-intensity physical activity; MVPA, moderate-to vigorous-intensity physical activity; *n*, number; SD, standard deviation; VPA, vigorous-intensity physical activity; $\dot{V}O_2$peak, peak oxygen consumption.

more in the exercise group, with a between-group difference of −4.4 [−5.7; −3.0] (ES: 0.64). Similarly, the % of $\dot{V}O_2$peak at LT-pre in the exercise group decreased comparably more, resulting in a between-group difference of −4.5 [−6.1; −2.9] (ES: 0.60). The exercise group had a larger decrease in $[La^-]_b$ at LT-pre, with a between-group difference of −0.7 [−0.9; −0.4] mmol/L (ES: 0.61).

During the LT test, the exercise group exhibited an overall mean reduction of 19% in $[La^-]_b$ from pre- to postintervention compared to a reduction of 4% in the control group, with between-group differences ($p \leq 0.05$) at treadmill inclines of 7%, 10%, 13%, and 16% (Figure 3).

3.3 | Adherence to the Exercise Intervention

A detailed overview of the participants' overall adherence to the planned intervention, as well as specific adherence rates to the frequency, intensity, and duration, are shown in Table 4.

The average total intervention duration (postfamiliarization) was 24.3 ± 5.9 weeks (111% of planned), and the achieved MET-min for the total intervention was 122% of the planned volume, totalling 11 116 ± 5455 MET min. On average, 186 ± 80 MET-min and 474 ± 233 MET-min were performed during each session and per week, respectively. Participants completed 2.6 weekly sessions, achieving 86% of the planned frequency. Specifically, 1.6 were interval sessions (78% of planned), 0.8 were circuit sessions (77% of planned), and 0.3 were alternative sessions.

Regarding intensity, 10.3 ± 5.2 min per session were spent at ≥80% of HRpeak (98% of planned). Specifically, this was 13.0 ± 5.6 min for interval sessions (116% of planned), 4.6 ± 4.9 min for circuit sessions (51% of planned), and 9.0 ± 12.5 min for alternative sessions (84% of planned). Including recovery bouts, the overall mean % of HRpeak was 73.2 ± 4.5 with a session RPE of 14.9 ± 1.7. Specifically, the mean % of HRpeak was 76.2 ± 4.5 for interval sessions, 68.1 ± 6.3 for circuit sessions, and 66.5 ± 8.9 for alternative sessions.

The average main session duration was 39.9 ± 11.8 min (135% of planned). Specifically, 36.6 ± 10.1 min for interval sessions (122% of planned), 36.5 ± 9.3 min for circuit sessions (128% of planned), and 71.5 ± 47.3 min for alternative sessions (242% of planned).

3.4 | Safety, Adverse Events, and Dropouts

The regular participant-coach communications gathered data regarding safety, adverse events, and dropouts. Of the 23 participants who withdrew from the study, none cited injuries from the exercise program as the reason. Five participants found the program too demanding, 11 withdrew due to health concerns unrelated to the program, and six for personal reasons.

Eighteen participants encountered minor injuries related to muscles (e.g., calf tightness or hamstring strain) or joints (i.e., exercises exacerbated pre-existing conditions such as knee or hip pain). Three participants struggled to exercise at the desired intensity following recovery from COVID-19. Additionally, three participants fell during outdoor interval sessions, leading to minor cuts and scrapes in one instance and hairline rib fractures in two instances. Notably, the falls resulting in rib fractures occurred on uneven ground (even though not recommended), a factor that should be carefully considered when prescribing exercise programs for older adults.

3.5 | Sensitivity Analysis

Across all outcomes, there was consistency between the intention-to-treat analysis and the original dataset analysis, with both yielding comparable results (Table S2). In the per-protocol sensitivity analysis, 16 participants from the exercise group who did not achieve an overall adherence level of ≥80% were excluded. The between-group differences remained consistent with the intention-to-treat analysis, showing: 2.0 [1.4; 2.6] mL/kg/min (ES: 0.39) and 0.13 [0.08; 0.17] L/min (ES: 0.24) for

TABLE 3 | Cardiorespiratory fitness pre- to postintervention within and between groups.

	Exercise			Control			Group difference	
Variables	**Pre mean [95% CI]**	**Post mean [95% CI]**	**Change mean [95% CI]**	**Pre mean [95% CI]**	**Post mean [95% CI]**	**Change mean [95% CI]**	**E vs. C mean [95% CI]**	**Effect size**
Max. CPET ($n=103$C:112E)								
$\dot{V}O_2$peak (mL/kg/min)	27.6 [26.9; 28.4]	29.0 [28.2; 29.8]	1.4 [1.0; 1.7]#	27.9 [27.1; 28.8]	27.5 [26.7; 28.4]	−0.4 [−0.8; −0.0]#	1.8 [1.2; 2.3]*	0.35
$\dot{V}O_2$peak (L/min)	2.22 [2.15; 2.28]	2.28 [2.22; 2.34]	0.07 [0.04; 0.10]#	2.24 [2.18; 2.31]	2.20 [2.14; 2.27]	−0.04 [−0.07; −0.01]#	0.10 [0.06; 0.15]*	0.20
LT-test ($n=100$C:109E)								
TMS preceding LT (n)	5.0 [4.7; 5.2] M: 5.6 [5.2; 5.9] F: 4.4 [4.1; 4.8]	5.7 [5.5; 5.9] M: 6.3 [6.0; 6.7] F: 5.2 [4.8; 5.5]	0.7 [0.6; 0.9]# M: 0.8 [0.5; 1.0]# F: 0.7 [0.5; 1.0]#	5.3 [5.1; 5.5] M: 5.8 [5.4; 6.1] F: 4.9 [4.6; 5.2]	5.4 [5.1; 5.7] M: 5.8 [5.4; 6.2] F: 5.1 [4.7; 5.4]	0.1 [−0.1; 0.3] M: 0.0 [−0.3; 0.3] F: 0.2 [−0.1; 0.4]	0.6 [0.3; 0.8]* M: 0.7 [0.3; 1.1]* F: 0.5 [0.1; 0.8]*	0.47
%HRpeak at LT-pre	89.8 [88.7; 91.0]	85.1 [83.8; 86.4]	−4.8 [−5.7; −3.8]#	90.1 [88.8; 91.4]	89.7 [88.2; 91.1]	−0.5 [−1.5; 0.6]	−4.4 [−5.7; −3.0]*	0.64
%$\dot{V}O_2$peak at LT-pre	89.4 [88.2; 90.6]	84.2 [82.8; 85.6]	−5.2 [−6.3; −4.0]#	89.5 [88.1; 90.8]	88.8 [87.2; 90.3]	−0.7 [−1.9; 0.6]	−4.5 [−6.1; −2.9]*	0.60
$[La^-]_b$ at LT-pre (mmol/L)	4.4 [4.2; 4.6]	3.2 [3.0; 3.4]	−1.3 [−1.5; −1.0]#	4.4 [4.2; 4.7]	3.8 [3.6; 4.1]	−0.6 [−0.8; −0.3]#	−0.7 [−0.9; −0.4]*	0.61

Note: Values from general linear regression models taking into account age, sex, and country of residence. Data are reported as estimated mean change with 95% CI for within-group changes and between-group differences in change.
Abbreviations: $[La^-]_b$, blood lactate concentration; C, control; CI, confidence interval; E, exercise; F, female; HRpeak, peak heart rate; LT, lactate threshold; M, male; n, number; TMS, treadmill stages; $\dot{V}O_2$peak, peak oxygen consumption.
*$p \leq 0.05$, significant difference between groups.
#$p \leq 0.05$, significant change from baseline within groups.

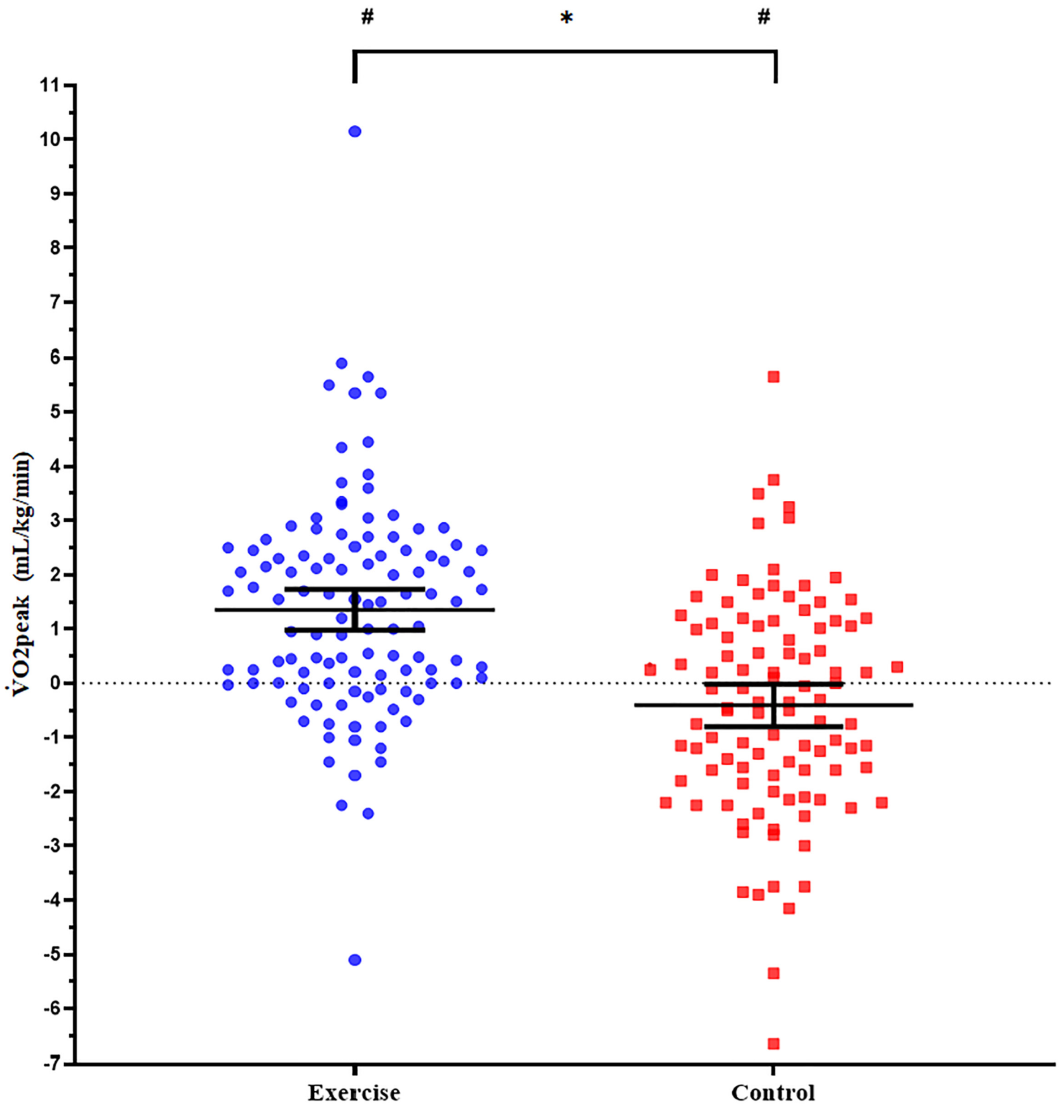

FIGURE 2 | Visualization of the change in $\dot{V}O_2$peak (mL/kg/min) from baseline. Each dot (exercise group) and square (control group) represent individual participant values. The solid horizontal lines indicate the mean change for each group, with the whiskers extending to show the 95% confidence intervals. *$p \leq 0.05$, significant difference between groups. #$p \leq 0.05$, significant change from baseline within groups.

relative and absolute $\dot{V}O_2$peak, respectively; 0.7 [0.4; 1.0] (ES: 0.54) for TMS preceding LT; −4.6 [−6.1; −3.1] (ES: 0.69) for % of HRpeak at LT-pre; −4.9 [−6.7; −3.0] (ES: 0.64) for % of $\dot{V}O_2$peak at LT-pre, and −0.7 [−1.1; −0.4] mmol/L (ES: 0.67) for $[La^-]_b$ at LT-pre (Table S3).

In the $\dot{V}O_2$max end criteria sensitivity analysis, 11 participants were excluded due to not meeting the age-adjusted end criteria of $[La^-]_b \geq 4.0$ or RER ≥ 1.0 on both test occasions. The results were similar to the intention-to-treat analysis, with between-group differences in $\dot{V}O_2$peak of 1.8 [1.2; 2.3] mL/kg/min (ES: 0.36) and 0.10 [0.06; 0.15] L/min (ES: 0.20), for relative and absolute $\dot{V}O_2$peak respectively (Table S4).

4 | Discussion

The present study shows that an easily accessible, equipment-minimal, home-based HIIT intervention can induce significant and clinically meaningful enhancements (i.e., >1 mL/kg/min in $\dot{V}O_2$peak) [34] in the cardiorespiratory fitness of healthy older adults. Over a six-month period, the exercise group exhibited significant improvements in all outcomes compared with the control group. Specifically, the exercise group enhanced $\dot{V}O_2$peak and TMS preceding LT compared with the control group. Moreover, the exercise group exhibited greater reductions in $[La^-]_b$, % of HRpeak, and % of $\dot{V}O_2$peak at LT-pre from pre- to postintervention compared with the control group. Notably, while all outcomes displayed significant between-group differences, the LT outcome showed a more pronounced magnitude of change (i.e., greater effect size) due to the exercise intervention than $\dot{V}O_2$peak (Table 3).

The home-based HIIT program led to a significant between-group difference in $\dot{V}O_2$peak change of 1.8 mL/kg/min compared with the control group, aligning with or surpassing findings from similar home-based studies in older adults. Specifically, Tarumi et al. [35] reported a between-group

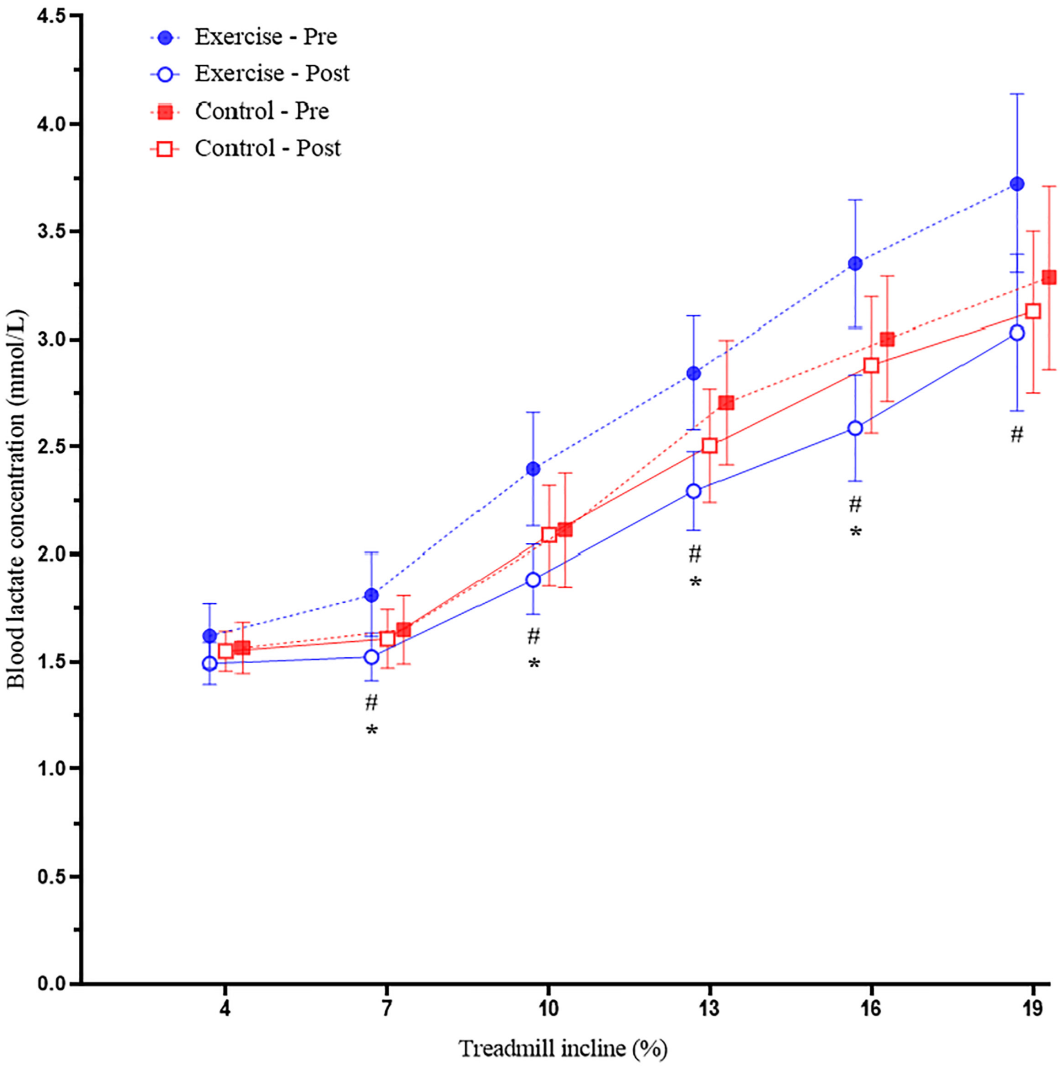

FIGURE 3 | Visualization of the changes in the lactate profile from baseline and between groups based on the incremental treadmill stages. The dots and squares represent mean values with 95% confidence intervals. *$p \leq 0.05$, significant difference between groups for the change from baseline (pre). #$p \leq 0.05$, significant change from baseline within groups. The figure represents all participants who completed at least three treadmill stages on both test occasions. Accordingly, the total number of participants progressively decreases from a treadmill incline of 10%–19%. Therefore, the figure illustrates submaximal $[La^-]_b$ across the treadmill inclines and does not represent specific lactate threshold determinations. A general linear regression model was used to assess the between-group differences in change and within-group changes at each stage.

difference in $\dot{V}O_2$peak change of ~1.4 mL/kg/min following a 1-year moderate-to-high-intensity aerobic exercise program. Furthermore, Stensvold et al. [23] demonstrated that $\dot{V}O_2$peak was 0.8, 0.7, and 0.3 mL/kg/min higher when combining MICT and HIIT intervention groups compared with controls after 1, 3, and 5 years, respectively, and 0.7 mL/kg/min higher in the HIIT group compared with both the control and MICT group after 5 years. Although the between-group difference in $\dot{V}O_2$peak change aligns with or exceeds those reported by the aforementioned studies, it is lower than the ~2.3 mL/kg/min enhancement reported by a systematic review and meta-analysis investigating supervised HIIT [36]. These differences could be attributed to the home-based nature of the present intervention, supported by the similar outcomes from the previously discussed home-based interventions [16, 35]. Furthermore, the within-group increase of 1.4 mL/kg/min (~5%) in the exercise cohort of the present study is lower than the expected 10% increase based on previous research [8, 18, 30]. It is commonly argued that adherence to home-based interventions is generally lower than supervised interventions [37]. Contrary to this notion, participants in the present study demonstrated an overall exercise adherence of 122% (i.e., participants performed more than the prescribed exercise volume). Furthermore, the per-protocol analysis (i.e., excluding participants with <80% overall adherence) showed a larger between-group difference in $\dot{V}O_2$peak change of 2.0 mL/kg/min (ES: 0.39), which is more comparable with the supervised HIIT interventions reviewed by Wu et al. [36]. Taken together, these data indicate that, like supervised HIIT interventions, home-based HIIT are indeed effective at improving cardiorespiratory fitness in older adults when performed with adequate adherence. It also highlights the need to objectively measure adherence to home-based interventions, as this could explain why previous studies report smaller training-induced changes in $\dot{V}O_2$peak.

TABLE 4 | Adherence to the exercise intervention.

Variables	Planned	Achieved Mean ± SD	% RDI Mean ± SD
Overall prescription—achieved intensity (MET value) × session duration (main session) × frequency			
MET-min total	8567	11 116 ± 5455	122 ± 59[a]
MET-min/session	130	186 ± 80	
MET-min/week	389	474 ± 233	
Frequency—sessions/week			
Overall	3.0	2.6 ± 0.6	85.6 ± 17.7
Interval sessions	2.0	1.6 ± 0.5	77.6 ± 25.2
Circuit sessions	1.0	0.8 ± 0.3	76.9 ± 29.1
Alternative sessions		0.3 ± 0.4	10.1 ± 14.3
Intensity—minutes per session spent >80% of HRpeak			
Overall	10.5	10.3 ± 5.2	97.7 ± 49.8
Interval sessions	11.3	13.0 ± 5.6	115.8 ± 49.4
Circuit sessions	9.0	4.6 ± 4.9	50.6 ± 54.6
Alternative sessions	10.5	9.0 ± 12.5	83.9 ± 118.7
Intensity—mean session HR including recovery bouts (session RPE, Borg 6–20)			
Overall	73.0	73.2 ± 4.5 (14.9 ± 1.7)	100.4 ± 6.2
Interval sessions	73.0	76.2 ± 4.5 (15.1 ± 1.8)	104.3 ± 6.2
Circuit sessions	73.0	68.1 ± 6.3 (14.4 ± 1.9)	93.3 ± 8.6
Alternative sessions	73.0	66.5 ± 8.9 (13.4 ± 2.3)	89.5 ± 17.0
Duration—main session duration in minutes			
Overall	29.5	39.9 ± 11.8	135.1 ± 39.9
Interval sessions	30.0	36.6 ± 10.1	121.9 ± 33.8
Circuit sessions	28.5	36.5 ± 9.3	127.9 ± 32.6
Alternative sessions	29.5	71.5 ± 47.3	242.4 ± 160.2

Note: Relative dose intensity (RDI) was calculated by comparing the total cumulative volume "achieved" to the "planned" cumulative volume, expressed as a percentage. An RDI of 100% signifies that the training intervention was executed with the intended volume, including frequency, intensity, and duration, as per the protocol.

Abbreviations: HRpeak, peak heart rate; MET, metabolic equivalent of task; min, minutes; RDI, relative dose intensity; RPE, rating of perceived exertion; SD, standard deviation.

[a]As a result of accounting for extended intervention periods in cases of sickness, minor injuries, or scheduling challenges, the calculated percentage is slightly lower than a direct calculation of the ratio between the achieved and planned doses.

Limited research has investigated the effects of HIIT on submaximal $[La^-]_b$ and LT among older adults; however, enhancements in these metrics could be highly significant for this population. For example, older adults typically conduct their daily activities at an intensity at or below LT rather than at $\dot{V}O_2$peak [11]. Moreover, efficient performance of most daily tasks is believed only to require a $\dot{V}O_2$peak of 18 mL/kg/min [13], a fitness level surpassed by ~98% of the participants in this study. In the present study, the exercise group exhibited an overall mean reduction of 19% in submaximal $[La^-]_b$ from pre- to postintervention compared to a reduction of 4% in the control group, with significant between-group differences at treadmill inclines ranging from 7% to 16%. Notably, as illustrated in Figure 3, the exercise group demonstrated higher baseline $[La^-]_b$ levels compared with the control group, which could be a result of higher initial $[La^-]_b$ responses in the exercise group and should, therefore, be considered when interpreting the results. However, the present study's findings align with a study by Morat et al. [38] that reported a mean reduction of 32% in submaximal $[La^-]_b$ after a 12-week Nordic walking program. Although the Nordic walking exercise intervention is not directly comparable to the present study, the achieved mean intensity (including recovery bouts) across all sessions was identical between interventions (73 ± 4% of HRpeak). Thus, these data highlight the potential of exercise interventions, including HIIT, to induce significant changes to submaximal $[La^-]_b$ in older adults, which may make a meaningful difference in their daily living activities.

Furthermore, the LT outcome showed a larger magnitude of change when comparing the effect sizes of the training-induced changes in $\dot{V}O_2$peak and LT in the present study (Table 3). This distinction between $\dot{V}O_2$peak and LT could be particularly relevant in the context of older adults, offering deeper insight into physiological adaptations to exercise interventions. While an increase in $\dot{V}O_2$peak of 1 mL/kg/min has been associated with a reduced risk of premature mortality [34], the present study's pronounced changes in LT might hold even more immediate implications for this age group. As previously emphasized, the intensity levels at which older adults typically conduct their daily activities align more closely with the sub-maximal LT test than with $\dot{V}O_2$peak [11]. This behavioral pattern suggests that while $\dot{V}O_2$peak is a crucial metric for long-term health outcomes, LT may offer a more immediate and concrete reflection of an older individual's functional capacity in their daily life. Thus, the more significant magnitude of change observed in the LT outcome in the present study (Table 3) could be of great importance as it may be more reflective of older adults' day-to-day activities and routines.

Another noteworthy aspect of the present study is the novel approach adopted to assess and report exercise adherence [22]. Traditional methods often rely on attendance and rates of lost-to-follow-up, which provide limited insight into important objective variables such as exercise intensity and volume [21, 22]. Moreover, in home-based interventions like the "Generation 100 study [23]" adherence to the prescribed FITT factors is often limited to self-reported exercise logs, which is susceptible to recall bias [24]. In the present study, a more comprehensive and objective method was used, ensuring an accurate representation of participants' adherence to the program. This novel approach ensures the credibility of reported adherence levels and sets a precedent for future studies, emphasizing the importance of accurate and objective reporting. Such methodological advancements are crucial in ensuring the reliability of findings and providing a clear picture of interventions' real-world applicability and effectiveness. By integrating these novel methods, the study further bridges the gap between research and practical application, ensuring that the reported benefits of the HIIT program are grounded in genuine participant engagement and adherence.

Although significant group-level improvements were observed for all outcome measures, there was considerable interindividual variability (i.e., Figure 2). This variability in cardiorespiratory fitness responses is consistent with findings by Williams et al. [13], who reported that high-volume HIIT elicited a responders rate of 31% when accounting for both the technical error of measurement (coefficient of variation of 5.6%) and the minimal clinically important difference (3.5 mL/kg/min). Following these findings, it is important to consider that individual responses to exercise can vary based on a multitude of factors, including genetics/heredity, training status, the homeostatic stress of each training session, habitual physical activity, sleep, and nutrition [39]. Along these lines, further exploration of how different exercise protocols align with individual responses is warranted. Moreover, although a significant group-level decrease was observed in $\dot{V}O_2$peak among the control group, several participants experienced improvements. These improvements could be a result of the Hawthorne effect, where the consequent awareness of being studied results in more physically active behaviors and should be a consideration for future research [40].

The findings from the present study strongly advocate for broader adoption of the equipment-minimal, easily accessible home-based HIIT program for older adults. The present study demonstrated that home-based HIIT induces significant and clinically meaningful improvements in cardiorespiratory fitness for older adults. Furthermore, home-based HIIT appears to induce more substantial beneficial changes in LT than $\dot{V}O_2$peak, suggesting LT is an essential metric when assessing exercise training-induced gains in cardiorespiratory fitness in older adults. Contrary to prior reservations about home-based interventions [37] and general skepticism toward HIIT [41], the present study observed high overall adherence levels during 6 months of home-based HIIT. The inherent advantages of the home-based HIIT program, such as minimal equipment requirements, no need for a gym membership, and the flexibility to take the program on the go, set the stage for its potential large-scale implementation.

4.1 | Limitations

While the study aimed to recruit participants with low physical activity levels, objective baseline assessments indicated that most were more physically active than previously self-reported (Table 2). Nonetheless, the average baseline $\dot{V}O_2$peak for males and females was lower than Norwegian reference data for this age group [42], indicating accurate recruitment in terms of baseline fitness level. The cardiorespiratory fitness assessment did not include a dedicated familiarization test prior to baseline testing, which may have affected the results despite efforts to mitigate potential learning effects through equipment familiarization. This approach was taken to balance the comprehensive nature of the present study's test battery against the practical and logistical considerations of participant burden. Furthermore, the collaboration between Norway and the UK, although advantageous for diverse participant inclusion, could have introduced variability in laboratory measurements and participant follow-up. To reduce the potential inter-rater bias, a comprehensive test protocol was established and pre-registered prior to the study, and the Norwegian test leader personally visited Birmingham to familiarize the UK test leader with all procedures. In addition, the two test leaders had regular contact to ensure similar handling of participants. Moreover, for the secondary outcome, posttest values of $[La^-]_b$, HR, and $\dot{V}O_2$ corresponding to the pretest LT stage were compared, including only participants who reached the same or higher LT stage at the posttest. While necessary for consistency in comparison, this exclusion criterion could be a limitation as it potentially skews the results towards those with more favorable responses. However, the majority of excluded participants were from the control group, suggesting that the between-group differences may have been more pronounced in favor of the exercise group if these participants could have been included. Furthermore, participants spent only 50% of the planned time within the desired HR zone during circuit sessions, mainly due to the complex nature of these sessions requiring extended familiarization. This highlights a limitation in our intervention design and emphasizes the need to consider older adults' familiarity with exercise protocols. Finally, the present study's participant sample comprised older adults aged 60–84 who were essentially nonexercising but relatively healthy and physically active. This specificity may limit the generalizability of the results to broader populations, including those with more severe functional impairments, low physical activity levels, or the oldest old, given the limited number of participants aged 80 years or older.

5 | Perspectives

The present study highlights the potential of home-based HIIT, advocating for broader implementation in public health and policy frameworks. The benefits observed in cardiorespiratory fitness demonstrate the effectiveness of HIIT in addressing one of the numerous health challenges an aging population presents [34, 43]. These findings are particularly significant given the successful international implementation of the exercise program, with the intervention proven effective and having high adherence levels in both Norwegian and UK populations.

Moreover, the high adherence levels observed in this study warrant a deeper exploration of the potential contributing factors. Understanding the motivational drivers, behavioral determinants, and support mechanisms facilitating the high adherence levels could provide valuable insights for designing future interventions. The objective should be to design programs that are not only scientifically effective but also deemed manageable by the target population.

However, transitioning from research findings to large-scale implementation presents multiple challenges. Future research should explore the barriers to widespread adoption, strategies to enhance scalability and assess the long-term sustainability of exercise programs, potentially enhancing interventions' real-world applicability.

In essence, this study lays a foundation for future research into HIIT's multifaceted adaptations and potential health benefits, aligning scientific inquiry with practical solutions to navigate the challenges of an aging population.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

All relevant data have been uploaded and are accessible via OSF Storage (osf.io/d7aw2).

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.