

**Mobile health pulmonary rehabilitation for people with chronic obstructive
pulmonary disease**

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ABSTRACT

Chronic obstructive pulmonary disease (COPD) is a highly prevalent chronic respiratory disease that is both preventable and treatable [1]. As one of the leading causes of disease burden and mortality worldwide [2], COPD has a significant economic and societal burden on healthcare systems and on people living with the condition [1]. Pulmonary rehabilitation (PR) is strongly recommended as an essential, evidence-based intervention that improves exercise capacity and health-related quality of life (HRQoL) in people with COPD [1, 3, 4]. However, significant barriers to access, uptake and completion of the program persist [5], limiting the widespread benefits and underscoring the vital need to explore alternative, effective modes of PR delivery that can overcome these challenges [5].

The evolution of digital technologies in healthcare has prompted the development and evaluation of telerehabilitation PR. This approach to PR delivery enables the direct or indirect remote supervision of people with COPD as they complete home-based PR programs [10]. Telerehabilitation PR provided through videoconferencing platforms (videoconferencing PR), web-based platforms (web-based PR) and mobile health (mHealth) applications (mHealth PR), to people with COPD has been explored in the literature and is summarised in **Chapter 1** of this thesis. To date, no randomised controlled trial has rigorously evaluated an mHealth PR program that included all essential components of PR [6]. To address this gap, the series of studies presented in this thesis have evaluated a comprehensive, mHealth PR program with all essential and desirable components of PR [6] in people with COPD.

The aim of the randomised controlled equivalence trial in **Chapter 2** was to determine if mHealth PR was equivalent to centre-based PR for improvements in exercise capacity and health status in people with COPD. Participants were randomised to either an eight-week mHealth PR program supported by the mobile pulmonary rehabilitation (m-PR™) application (app) or an eight-week centre-based PR program. Co-primary outcomes were change in the six-minute walk distance (6MWD) and the COPD Assessment Test (CAT) score, with equivalence margins set at the minimum clinically important difference (MCID) of ± 30 m for the 6MWD [7] and ± 2 points [8] for the CAT score. Ninety participants were randomised, 44 to the mHealth PR group and 46 to the centre-based PR group. Results showed that in

people with moderate to severe COPD with adequate technology skills, mHealth PR was superior to centre-based PR for improvements in health status (mean difference [MD] -4.9 points, 95% confidence interval [CI] -7.2 to -2.6), and equivalent for improvements in exercise capacity (MD 13 m, 95% CI -6 to 31). Exercise session adherence was similarly high in both the mHealth PR (86%) and centre-based PR groups (87%) and no serious adverse events related to the study were reported. The findings from this study have demonstrated that mHealth PR could be effective as a management option for people with COPD with adequate digital literacy.

The single-arm analysis in **Chapter 3** was the first study to comprehensively characterise the engagement behaviour and evaluate adherence to an mHealth PR app in people with COPD. mHealth PR participants in Chapter 2, excluding dropouts, were included in this analysis (n = 38). Participant interactions with the m-PR™ app were automatically recorded by the app (system-recorded data) and analysed to determine engagement and adherence trends to the overall m-PR™ app and to certain app features. The results demonstrated that people with COPD were highly engaged and adherent to the m-PR™ app overall and to the individual weekly app tasks. All 38 mHealth PR participants engaged with the m-PR™ app at least once, accessing the app on a mean (SD) 4.8 (0.3) days per week. Low attrition rates were found with 92% of participants still using the app in the eighth program week. All participants engaged with the exercise program, education and exercise videos, and symptom monitoring questionnaires. Adherence rates were highest to the exercise program (overall = 87% [n = 33], endurance exercises = 84% [n = 32], resistance exercises = 87% [n = 33]) and lowest to the daily symptom questionnaires (13% [n = 5]). A decline in engagement and adherence was seen over time with the informational videos and symptom monitoring tasks. The findings from the study demonstrated that people with COPD can engage with and adhere highly to multiple components of an mHealth PR app.

The secondary analysis in **Chapter 4** was the first to determine the resource usage costs and carbon footprint of delivering an mHealth PR program to people with COPD when compared to centre-based PR. Data was collected from the participants and PR programs examined in the study in Chapter 2. Resource usage costs from a societal perspective were measured in 2024 Australian dollars (AUD) and included costs to the healthcare provider and to the participant. Greenhouse gas (GHG)

emissions were measured in kilograms of carbon dioxide equivalent (kgCO_{2e}) and were categorised as Scope 1, Scope 2 and Scope 3 emissions. A base analysis was conducted that determined the resource usage costs and GHG emissions associated with conducting the randomised controlled trial in Chapter 2. In addition, a scenario analysis was undertaken, which can be used to inform real-world clinical practice, to determine the resource usage costs and GHG emissions if an mHealth PR program was implemented into clinical practice in the Northern Sydney Local Health District (NSLHD). Results from the base analysis showed that in research conditions, there were no significant differences between mHealth PR and centre-based PR for resource usage costs (MD \$48, 95% CI -\$16 to \$113) and GHG emissions (MD -21 kgCO_{2e}, 95% CI -51 kgCO_{2e} to 8 kgCO_{2e}) per participant. The results from the scenario analysis, which is relevant to policymakers and program implementation, demonstrated that if mHealth PR was implemented into clinical practice, a resource usage cost-saving of \$137 (95% CI \$86 to \$189) and a reduction in GHG emissions of 36 kgCO_{2e} (95% CI 8 kgCO_{2e} to 63 kgCO_{2e}) per participant would be found, equivalent to \$58,088 and 13,838 kgCO_{2e} per year across two NSLHD PR sites.

A summary of the main findings of this thesis and the limitations, clinical implications and suggestions for future research are discussed in **Chapter 5**.

The studies contained in this thesis have demonstrated that in people with moderate to severe COPD who have adequate technology skills:

- i) mHealth PR could be a clinically effective option for people with COPD but should contain all essential and desirable components of PR;
- ii) people with COPD can engage and adhere highly to multiple components within an mHealth PR app; and
- iii) mHealth PR programs could be implemented into clinical practice to optimise savings in resource usage costs and GHG emissions.

Overall, the series of studies in this thesis have demonstrated that mHealth PR, with all essential and desirable components of PR, could be offered as an alternative option to people with moderate to severe COPD who have adequate technology skills.

STATEMENT OF ORIGINALITY

This is to certify that to the best of my knowledge, the content of this thesis is my own work. This thesis has not been submitted for any degree or other purposes.

I certify that the intellectual content of this thesis is the product of my own work and that all the assistance received in preparing this thesis and sources have been acknowledged.

Sarah Brown

15th August 2025

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AUTHORSHIP CONTRIBUTION STATEMENT

Candidate Name: Sarah Brown

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In accordance with the University of Sydney Higher Degree Research policy, this thesis contains both a manuscript submitted for publication and stand-alone chapters. I, Sarah Brown, led the included study and chapters, which were conducted under the supervision of Dr Sally Wootton, Dr Marita Dale, Associate Professor Michelle Cunich, Professor Andrew Chan, Associate Professor Zoe McKeough and in collaboration with other co-authors. The specific contributions of each author for each chapter are described below.

Chapter 1: Literature Review

This chapter was written by Sarah Brown with feedback from Zoe McKeough, Sally Wootton, Marita Dale, Michelle Cunich and Andrew Chan.

Chapter 2: Mobile Health Pulmonary Rehabilitation (m-PR): a Randomised Controlled Equivalence Trial

Sarah Brown was responsible for conception and design of research, data collection and management, analysis and interpretation of findings, and writing the manuscript and critical appraisal of content.

Sally Wootton, Marita Dale, Andrew Chan, Michelle Cunich, Zoe McKeough and co-authors contributed to the conception and design of the study and provided feedback on the manuscript draft.

Chapter 3: Engagement and adherence to a mobile health pulmonary rehabilitation (m-PR) application: a single-arm analysis of a randomised controlled trial

Sarah Brown was responsible for conception and design of research, data collection and management, analysis and interpretation of findings, and writing the manuscript and critical appraisal of content.

Sally Wootton, Marita Dale, Andrew Chan, Michelle Cunich, Zoe McKeough and co-authors contributed to the conception and design of the study and provided feedback on the manuscript draft.

Chapter 4: Mobile health pulmonary rehabilitation (m-PR) compared to centre-based pulmonary rehabilitation in people with COPD: a comparison of resource usage costs and greenhouse gas emissions

Sarah Brown was responsible for conception and design of research, data collection and management, analysis and interpretation of findings, and writing the manuscript and critical appraisal of content.

Sally Wootton, Marita Dale, Andrew Chan, Michelle Cunich, Zoe McKeough and co-authors contributed to the conception and design of the study and provided feedback on the manuscript draft.

Chapter 5: Discussion

This chapter was written by Sarah Brown with feedback from Zoe McKeough, Sally Wootton, Marita Dale, Michelle Cunich and Andrew Chan.

I attest that the statements above are correct

Sarah Brown

15th August 2025

As the research supervisor of the above candidate, I confirm that the authorship attributed statements above are correct:

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Date: 15th August 2025

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- Northern Sydney Local Health District
- The University of Sydney
- Better Breathing Foundation
- Lung Foundation Australia

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ABBREVIATIONS

Abbreviation	Definition
\$	Dollars
£	British Pounds
€	Euros
1minSTS	One-Minute Sit-To-Stand Test
2WD	Two-wheeled drive
5STS	Five-Times Sit-To-Stand Test
6MWD	Six-Minute Walk Distance
6MWT	Six-Minute Walk Test
ABS	Acrylonitrile butadiene styrene
AI	Artificial intelligence
AE	Adverse event
App	Application
ATS	American Thoracic Society
AUD	Australian dollars
AusLCI	Australian national Life Cycle Inventory database
BMI	Body Mass Index
CAT	COPD Assessment Test questionnaire
CB-PR	Centre-based pulmonary rehabilitation group
CCQ	COPD Clinical Questionnaire
CG	Comparison group
CI	Confidence interval
CO ₂ e	Carbon dioxide equivalent
CONSORT	Consolidated Standards of Reporting Trials
COPD	Chronic obstructive pulmonary disease
CRQ	Chronic Respiratory Disease Questionnaire
CRQ-D	Chronic Respiratory Disease Questionnaire Dyspnoea domain
CSES	COPD Self-Efficacy Scale
DCCEEW	Department of Climate Change, Energy, the Environment and Water
EF	Emission factor
EQ-5D	European Quality of Life Five-Dimension questionnaire
EQ-5D VAS	EQ-5D Visual Analogue Scale

ESWT	Endurance Shuttle Walk Test
EVA	Ethylene Vinyl Acetate
Ex	Exercise
Ex-SRES	Exercise Self-Regulatory Efficacy Scale
FEV ₁	Forced expiratory volume in 1 second
FEV ₁ /FVC	FEV ₁ as a percentage of forced vital capacity
FTE	Full-time equivalent
FVC	Forced vital capacity
GHG	Greenhouse gas
GOLD	The Global Initiative for Chronic Obstructive Lung Disease
GSES	General Self-Efficacy Scale
Gsm	Grams per square metre
HCP	Healthcare professional
HRQoL	Health-related quality of life
IG	Intervention group
iOS	iPhone operating system
ISWT	Incremental Shuttle Walk Test
ITT	Intention-to-treat
IQR	Interquartile range
Kg	Kilograms
KgCO _{2e}	Kilograms of carbon dioxide equivalent
Km	Kilometres
kWh	Kilowatt-hour
L	Litres
LPA	Low-intensity physical activity
LTOT	Long term oxygen therapy
m	Metres
MCID	Minimum clinically important difference
MD	Mean difference
mHealth	Mobile health
Mins	Minutes
mL	Millilitres
mMRC	Modified Medical Research Council dyspnoea scale

m-PR™	The Mobile Pulmonary Rehabilitation application
m-PR	mHealth pulmonary rehabilitation group
MVPA	Moderate to vigorous physical activity
N	Number of participants
N/A	Not applicable
n.m	Not measured
NSLHD	Northern Sydney Local Health District
NSW	New South Wales
OR	Odds ratio
OS	Operating system
RCT	Randomised controlled trial
RPE	Rate of perceived exertion
PA	Physical activity
PACES	Physical Activity Enjoyment Scale
PEDro	Physiotherapy Evidence Database
PET	Polyethylene terephthalate
pMDI	Pressurised metered-dose inhalers
PR	Pulmonary rehabilitation
PRAISE	Pulmonary Rehabilitation Adaptation Index for Self-Efficacy
PVC	Polyvinyl chloride
®	Registered trademark
s	Seconds
SD	Standard deviation
SF-12 PCS	12-item Short Form survey physical components section
SF-36	36-item Short Form Health Survey
SGRQ	St George's Respiratory Questionnaire
SMAS-30	Self-Management Ability Scale – 30 items
SpO ₂	Saturation of peripheral oxygen
STROBE	Strengthening the Reporting of Observational Studies in Epidemiology
SUS	System Usability Scale
SUV	Sport utility vehicle
TM	Trademark

UK	United Kingdom
USA	United States of America
USD	USA dollars
u-MARS	Mobile Application Rating Scale: User Version
VAS	Visual Analogue Scale
VR-12	Veterans RAND 12-item health survey

PUBLICATIONS, PRESENTATIONS AND AWARDS

Submitted manuscript

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Published Abstracts

- **Brown, S.**, Wootton, S., Dale, M., Alison, J., Chan, A., Varnfield, M., Yang, I., Cunich, M. & McKeough, Z (2024). Is mobile health pulmonary rehabilitation (m-PRTM) equivalent to centre-based pulmonary rehabilitation for people with COPD? A randomised controlled equivalence trial. *Intern Med J*, 55: 5-193.
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Brown, S. (2025). Ann Woolcock New Investigator Award – Finalist at The Australia & New Zealand Society of Respiratory Science and The Thoracic Society of Australia and New Zealand (ANZSRS/TSANZ) Annual Scientific Meeting for Leaders in Lung Health & Respiratory Science; March 24 2025, for oral presentation titled *Is mobile health pulmonary rehabilitation (m-PRTM) equivalent to centre-based pulmonary rehabilitation for people with COPD? A randomised controlled equivalence trial*.

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Other authored papers during the candidature

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CHAPTER ONE

BACKGROUND

RATIONALE OF THE THESIS

Chronic obstructive pulmonary disease (COPD) affects approximately 10% of the global population and remains a leading cause of disease burden and mortality [1], with the prevalence and burden expected to rise due to ageing populations [9, 10] and persistently high rates of tobacco smoking [9, 10] and air pollutants [11, 12]. Pulmonary rehabilitation (PR) is strongly recommended as an essential, non-pharmacological intervention for people with COPD [1, 3, 4] with Level A evidence that PR improves exercise capacity, HRQoL and symptoms in people with stable COPD when compared to standard care [1]. However, significant barriers to access, uptake and completion of PR limit the widespread benefits of the program. PR is predominately delivered as a centre-based program [3, 13, 14] and as such, barriers include those associated with geographical location, transport and program infrastructure such as staffing availability, space and equipment [5]. A recent American Thoracic Society (ATS) clinical practice guideline [4] has recommended that people with COPD should be offered the option of telerehabilitation PR as a strategy to overcome some of these barriers.

Telerehabilitation PR harnesses the use of digital technologies to support the remote delivery of PR in people's homes [10]. Direct or indirect supervision during telerehabilitation PR programs can be supported using videoconferencing platforms (videoconferencing PR), web-based platforms (web-based PR) and mHealth applications (mHealth PR). The widespread availability of smartphone technologies [15], along with offline capabilities gives mHealth PR certain advantages over videoconferencing PR and web-based PR. The results from two randomised controlled trials [16, 17] suggest that mHealth PR could be safe and no different to centre-based PR for improvements in exercise capacity and health status in people with COPD. However, to date there have been no randomised controlled trials that have rigorously investigated an mHealth PR program that contained all essential components of PR [6] or investigated the financial and environmental impacts. To address this gap, the series of studies contained in this thesis aimed to determine

the clinical effectiveness of an mHealth PR program with all essential components of PR when compared to centre-based PR, evaluate engagement and adherence to multiple app components, and compare the resource usage and environmental costs of mHealth and centre-based PR programs when delivered to people with COPD.

OVERVIEW OF CHRONIC OBSTRUCTIVE PULMONARY DISEASE

Pathophysiology

Chronic obstructive pulmonary disease (COPD) is a heterogeneous and progressive lung disease that is characterised by persistent lung airflow limitation and symptoms of dyspnoea, cough and/or sputum production [1]. COPD is typically caused by environmental exposures to toxic particles and gases, most commonly from tobacco smoking and air pollution, that trigger an inflammatory response in the lungs and subsequently lead to abnormalities of the airways (with or without chronic bronchitis) and/or lung parenchyma (e.g. emphysema) [1]. Physiological abnormalities of the lungs lead to a range of respiratory and non-respiratory symptoms experienced by people with COPD [18] that can manifest in early stages of the disease [1].

Symptoms

Dyspnoea and fatigue are the most commonly reported symptoms in people with COPD [18]. Actions that increase ventilatory requirements, such as the performance of activities of daily living or exercise, can trigger or increase the intensity at which dyspnoea is experienced [19]. A reduction in physical activity to avoid symptoms of exertional dyspnoea and fatigue lead to a downward spiral of worsening symptoms, skeletal deconditioning and physical inactivity in people with COPD [19-22].

Alongside symptoms of dyspnoea and fatigue, skeletal muscle dysfunction is prevalent in people with COPD and has a profound impact on exercise intolerance [20]. An interplay of physical inactivity, systemic inflammation, oxidative stress, nutritional imbalance and hypoxaemia contributes to the aetiology of skeletal muscle dysfunction [21] and most notably presents as atrophy and muscle weakness [20]. Skeletal function is further compromised during exacerbations of COPD as a result of systemic inflammation, reduced physical activity and exposure to corticosteroids [20].

Exacerbations of COPD, marked by the acute worsening of respiratory symptoms that require increased therapy, are significant complications of the disease [23]. Exacerbations can be triggered by respiratory infections or environmental pollutants [1], resulting in increased airway and systemic inflammation and hyperinflation that worsen symptoms of dyspnoea [24]. Exacerbations and related hospitalisations significantly impact the lives of people with COPD [25]. Recognising symptoms and the risk of exacerbations is necessary for COPD diagnosis, severity classification and management [23].

Diagnosis

In addition to the presence of symptoms and a history of risk factors, the finding of airflow obstruction from spirometry testing (forced expiratory volume in 1 second [FEV₁] / forced vital capacity [FVC] < 0.7) that is not fully reversible with bronchodilator treatment confirms the diagnosis of COPD [1]. The Global Initiative for Chronic Obstructive Lung Disease (GOLD) [1] stratifies airflow severity into four grades by comparing measured airflow obstruction (FEV₁) to predicted normative data from healthy population studies. Disease severity is typically classified by considering the severity of airflow limitation, symptoms and frequency of exacerbations [23]. Despite COPD being a common, preventable and treatable disease, under-recognition and misdiagnosis leads to a significant global burden on society [1].

Burden

Prevalence

The prevalence of COPD is estimated to be at least 10% of the global population [1]. Local rates of tobacco smoking; occupational exposure to dusts, fumes and gases; and outdoor and household air pollution are important risk factors for COPD [26, 27]. In 2022, there were approximately 638,000 (2.5%) people in Australia diagnosed with COPD, with higher prevalence amongst First Nations Australians; people aged over 55 years; and those living in lower socioeconomic, regional or remote areas [28]. With ageing populations in high-income countries and persistently high rates of tobacco smoking [9, 10] and air pollutants [11, 12] in low- and middle-income countries, the prevalence and burden of COPD is expected to rise.

Disease burden and mortality

Despite being a preventable and treatable condition, COPD is the eighth leading cause of disease burden and the fourth leading cause of mortality worldwide, contributing to 3.5 million deaths in 2021 [2]. Physical inactivity and exacerbations of COPD are strong predictors of mortality [1, 29] and worsen as disease severity increases [30, 31]. Exacerbations that result in hospitalisation are associated with a 6.7% in-hospital mortality rate [32], with those surviving admissions remaining at a high risk of re-admission and death [33-37]. The impact of exacerbations and hospital admissions imposes a considerable burden on people with COPD and the healthcare system, with people in Australia living in lower socioeconomic, and regional, rural and remote areas, experiencing a greater burden of disease and higher mortality rates than the national average [28].

Economic burden

COPD has a significant global economic burden [38]. There are substantial yearly direct costs of COPD on healthcare systems internationally, with the European Union and the United States of America (USA) incurring 48 billion Euros (€) [39] and \$40 billion USA dollars (USD) [40], respectively. In Australia, the treatment and management of COPD cost the healthcare system \$1.7 billion AUD in 2020-21 [41]. COPD is the second leading cause of preventable hospital admissions for chronic diseases in Australia [42], with hospital services representing 58% of the total national COPD expenditure [41]. Compounding this, healthcare utilisation and medication costs increase as disease severity worsens [43, 44]. In addition to direct costs, indirect costs from reduced labour productivity and early retirement have been shown to be greater in people with COPD [45-47] compared to the general population and these costs extend to their family caregivers [48]. The economic burden is expected to grow, particularly in low- and middle-income countries as COPD prevalence is rising more rapidly than in high-income countries [38, 47]. Recognising the economic impact of COPD is crucial for policymakers when attempting to prioritise investments in the effective management of the disease in their countries [38].

Environmental burden

The environmental impact of COPD is not fully understood. Measuring the environmental impact of health care is a novel concept, with global efforts to understand interactions between climate change and healthcare systems only coming into focus in the past decade [49]. Climate change trends indicate rising temperatures in the Earth's atmosphere, oceans and lands, which is largely attributed to the reflection of radiation back to the Earth's surface by water, clouds and GHGs, known as the greenhouse effect. Human activity, through the burning of fossil fuels, agriculture, transportation and deforestation has enhanced the greenhouse effect by emitting increasing amounts of GHGs [50] such as carbon dioxide, nitrous oxide and methane. Each GHG has a different effect on the climate [51] that is quantified by the global warming potential index [52]. The carbon dioxide equivalent (CO₂e) is a measure that allows the comparison of GHG emissions by multiplying the weight of GHG by their respective global warming potential index [50] and is used to calculate a 'carbon footprint'. The term 'carbon footprint' is widely used in business, government, media and scientific literature but has been defined inconsistently [53]. To account for GHGs beyond carbon dioxide, and to reflect the broad application of carbon footprint assessments [54], 'carbon footprint' is defined in this thesis as the total GHG emissions directly or indirectly associated with an activity, product, service, company or country.

Understanding the carbon footprint of healthcare systems will assist in global efforts to reduce the negative effects of global warming. Health care is responsible for 5% of total GHG emissions worldwide [55] and 7% of Australia's total carbon footprint [56]. Yet despite global efforts to meet the goals of the Paris Agreement [57], health care GHG emissions have increased by 36% since 2016 [58]. This highlights an urgent need to shift the focus of healthcare research towards identifying and minimising the impact of healthcare services on the environment.

Management

Pharmacological treatments

COPD clinical practice guidelines [1, 23] recommend that the reduction of symptoms and future risk of exacerbations should be the key treatment goals when managing people with COPD. Pharmacological treatments can be delivered to lower the

severity and frequency of symptoms and exacerbations in stable COPD, and to reduce the negative impact during exacerbations [1]. Inhaled bronchodilators, inhaled corticosteroids, or a combination of the two are recommended as part of initial pharmacological treatment for people with stable COPD to alleviate symptoms and reduce exacerbation risk [1, 23].

Non-pharmacological treatments

Non-pharmacological treatments play an important role in the management of stable COPD and the prevention of exacerbations. Smoking cessation, which can be achieved using non-pharmacological and pharmacological treatments, is considered essential in the management of people with COPD, regardless of disease severity [1]. Vaccinations, such as influenza and pneumococcal vaccinations, successfully decrease the frequency of exacerbations and can also be delivered at any stage of the disease and should be directed by local guidelines [1]. Oxygen therapy and non-invasive ventilation can be used to manage certain people with severe COPD or during exacerbations of COPD that result in hospitalisation [1, 23].

Education on the use of pharmacological and non-pharmacological treatment, as well as disease-specific education, management of symptoms and end-of-life issues, are some examples of education topics that can be provided to people with COPD. Education sessions can be provided through group-based or individual sessions and can deliver generic information and advice or personalised self-management education. Didactic education sessions are likely insufficient at improving health outcomes such as HRQoL, exercise capacity and healthcare utilisation [59] and are therefore not recommended for people with COPD [1, 23]. There is limited evidence that education alone achieves behaviour change [60]. Whereas self-management interventions, which include iterative interactions between people with COPD and healthcare professionals, aim to motivate, engage and support people with COPD to positively adapt health behaviours and develop skills to better manage their disease, [61] and likely improve HRQoL and lower risk of a respiratory-related hospital admission [62, 63]. Self-management interventions have been recommended for people with COPD [1, 23] and can be facilitated through PR programs [6, 64].

Regular exercise training, promotion of increased physical activity levels and participation in PR are strongly recommended non-pharmacological interventions for

people with COPD [1]. Physical activity, defined as any bodily movement that is produced by skeletal muscles and results in energy expenditure [65], is commonly lower in people with COPD than in healthy aged-matched individuals [66]. Exercise training is a subset of physical activity and is characterised by planned, structured and repetitive movements for the purpose of improving or maintaining physical fitness [65]. The frequency, intensity, time, type, volume and progression of exercise, known as the FITT-VP principle [67], can be tailored to account for the individual needs and goals of people with COPD [68]. Exercise training has been linked to a reduction in exercise-induced lactic acidosis and an increase in skeletal muscle oxidative capacity in people with COPD [69, 70]. As outlined in Figure 1.1, PR is a comprehensive program that incorporates exercise training as a key component amongst other non-pharmacological program components. PR is strongly recommended for people with COPD to improve exercise capacity and HRQoL, and reduce exacerbations of COPD [1, 23] and is explored further in the subsequent section of this chapter.

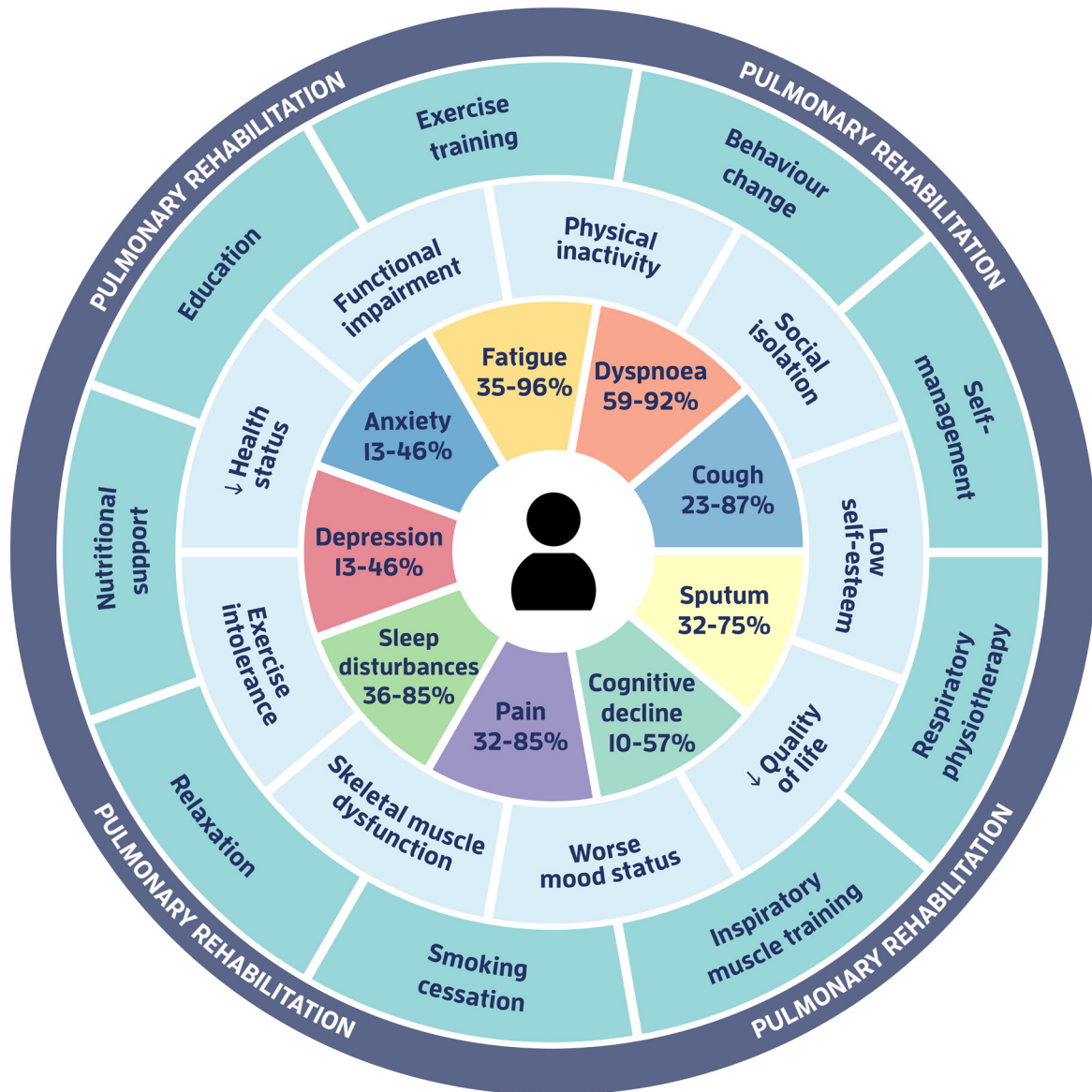


Figure 1.1. Overview of COPD symptoms, known extra-pulmonary precipitating and perpetuating factors, and PR intervention components. Adapted from Machado et al. 2021 [18].

PULMONARY REHABILITATION IN PEOPLE WITH STABLE COPD

Definition

Pulmonary rehabilitation is defined as a comprehensive and individualised program that, following a thorough assessment, delivers interventions that are designed to improve the physical and psychological condition of people with chronic respiratory disease and promote the long-term adherence to health-enhancing behaviours [64]. The majority of evidence supporting the effectiveness of PR is in people with stable COPD [71] or following an exacerbation of COPD [72]. Workshop reports [6] and PR clinical guidelines [3, 73, 74] have suggested components which should be included in PR programs. International experts, through a detailed Delphi workshop report published by the American Thoracic Society (ATS) [6], has been the most recent to identify the essential and desirable components of PR. The components relevant to people with COPD are outlined in Figure 1.2.

The authors of the ATS workshop report [6] concluded that all 13 essential components must be delivered as part of any PR program, regardless of program model. Exercise training is a cornerstone of PR [6, 23, 64], and it is necessary that exercise programs are individually prescribed and progressed, and include both endurance and resistance training [6]. A comprehensive assessment, and experienced and trained healthcare professionals are also considered essential. The inclusion of desirable components, such as education and self-management training, is dependent on local resources [14, 75], the healthcare system organisation, and the individual needs, goals and preferences of people with COPD attending the program [6].

Internationally, PR program components and structure differ considerably [14]. In Australia, most PR programs are funded through the public health system for non-admitted participants and are centre-based PR programs conducted in either a hospital or community centre exercise gym [3, 13]. Programs are typically delivered as an eight-week program with two supervised, group-based exercise sessions per week [3, 13]. In order to meet recommendations for PR session frequency [64] without placing additional demand on healthcare system resources, participants are often encouraged to perform unsupervised exercise training sessions in their own time each week [13, 23]. A national survey of PR programs in Australia [13] found

that the majority of programs satisfied the essential components relating to exercise and HRQoL assessments, although the inclusion of other essential assessments was either low (nutritional status) or unclear (dyspnoea and occupation status) [13].

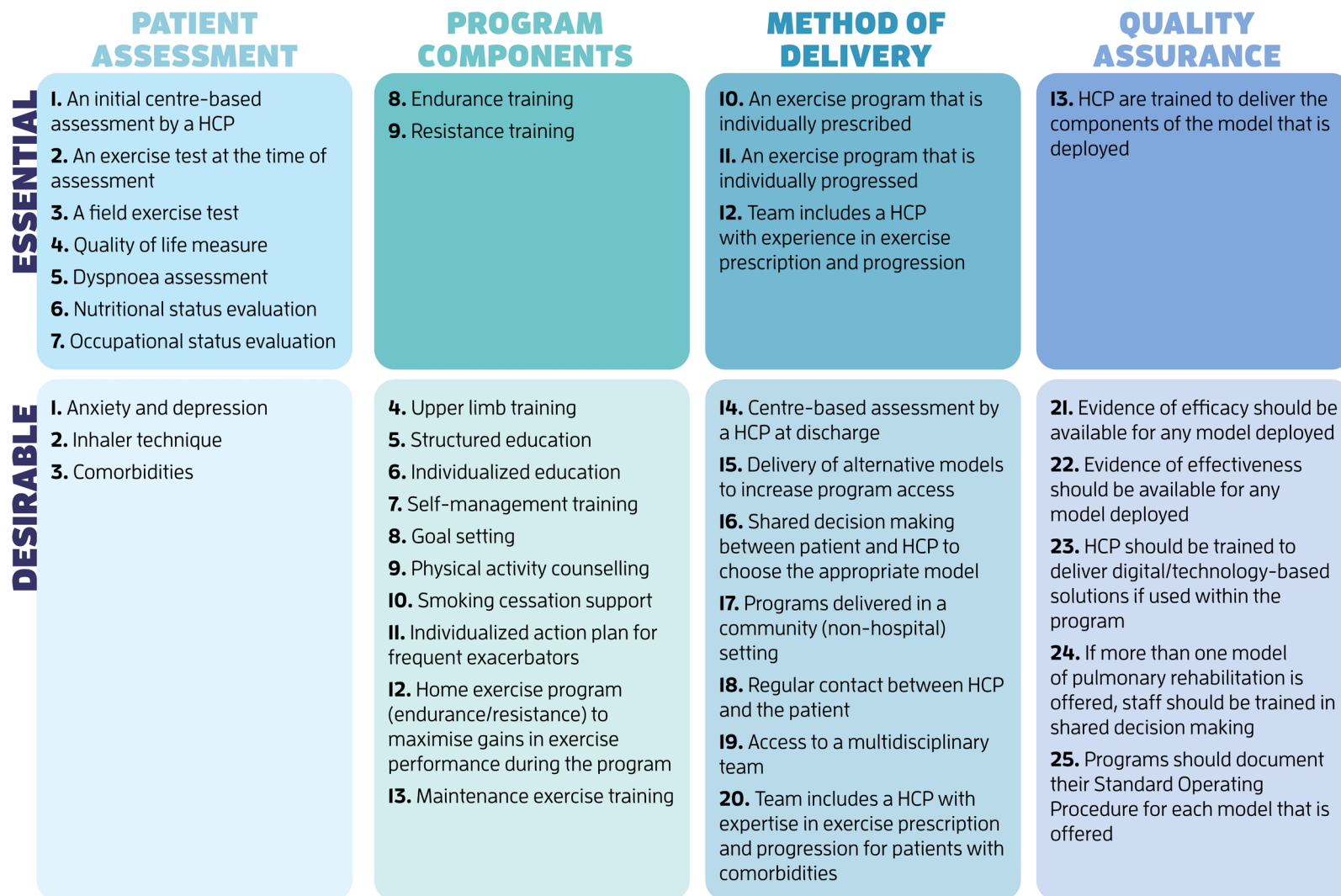


Figure 1.2. Essential and desirable components of PR (adapted from Holland et al 2021 [6]). Airway clearance technique for bronchiectasis and cystic fibrosis were excluded from desirable components as these are not relevant for people with COPD. HCP: healthcare professional

Effects of centre-based pulmonary rehabilitation

As a multi-component intervention, PR is designed to improve a range of outcomes for people with COPD. Although there are many potential beneficial outcomes from PR, the effects of PR on exercise capacity, HRQoL, dyspnoea, health status, physical activity and self-efficacy, and the economic and environmental impacts of PR, will be explored in detail in the following sections as these align with the outcomes of this thesis.

Exercise capacity

Exercise training is a key component of PR and measurements of exercise capacity are important to determine the clinical efficacy of the program. Although cardiopulmonary exercise testing is the gold standard for assessing cardiorespiratory fitness, field walking tests are more readily available and demonstrate good construct validity [7]. The most common field walking tests are the: i) Six-Minute Walk Test (6MWT) which is a self-paced walking test used to assess functional exercise capacity, ii) Incremental Shuttle Walk Test (ISWT) which is an externally paced walk test used to assess maximal cardiopulmonary exercise capacity, and iii) Endurance Shuttle Walk Test (ESWT) which is used to assess endurance exercise capacity [7]. These field walking tests are frequently used to evaluate changes in exercise capacity following PR.

A comprehensive Cochrane review by McCarthy and colleagues [71] compared PR to standard care in people with stable COPD. The aims of the review were to compare the effects of PR to standard care on exercise capacity and HRQoL in people with stable COPD. A total of 65 randomised controlled trials with a combined 3822 participants were included in the meta-analyses. Participants were people with mild to very severe COPD attending PR programs with a median follow-up time of 12 weeks. There were a variety of settings used in these studies, from hospital inpatient and outpatient centre-based settings to the use of home-based and community settings (e.g. private physiotherapy practices and primary care).

The Cochrane review by McCarthy and colleagues [71] found moderate-to-very low quality evidence that PR significantly improves functional exercise capacity in people with stable COPD. Pooled results from 38 randomised controlled trials found a statistically significant improvement in functional exercise capacity from PR, as

measured using the 6MWD, by 44 metres (m) (95% CI 33 to 55, number of participants [n] = 1879, very low quality) which exceeded the proposed MCID of 30 m [7]. Likewise, statistically significant improvements in ISWT (MD 40 m, 95% CI 33 to 55, n = 694, moderate quality) were found from the pooled effects of eight studies. The comprehensive analysis of the Cochrane review [71], with small sample sizes and narrow CI around the mean estimate, support the validity and reliability of the findings that PR effectively improves functional exercise capacity in people with stable COPD.

A comparison of the effects on exercise capacity when delivering PR programs with or without education or self-management interventions was not conducted by McCarthy and colleagues [71]. Only one high-quality randomised controlled trial [76] has compared PR with exercise training and disease-specific education to exercise training alone and found no differences between programs for changes in 6MWD (MD 16.5 m, 95% CI -9.0 to 41.9, p = 0.21). Conversely, in a placebo-controlled randomised controlled trial of moderate quality [77], the addition of exercise training and bronchodilator use to a self-management behaviour modification program significantly improved 6MWD by 27 m (p = 0.007) compared to the delivery of a self-management program alone. Although the authors did not differentiate between the effects of exercise training and bronchodilator use, the results from these trials [76, 77] highlight the key role exercise training plays in PR for improving exercise capacity in people with COPD.

Health-related quality of life

Measuring HRQoL is important to quantify symptom burden and to guide interventions in people with COPD. Common generic measures of HRQoL include the self-administered 36-item Short Form Health Survey (SF-36) [78] and the European quality of life five-dimension (EQ-5D) [79] questionnaire which allow broad comparisons of HRQoL across different diseases. The most frequently used disease-specific HRQoL questionnaires are the St George's Respiratory Questionnaire (SGRQ) [80] and the Chronic Respiratory Disease Questionnaire (CRQ) [81] which measure HRQoL across multiple health domains and have been validated in people with COPD following PR [80, 82].

Findings from the Cochrane review by McCarthy and colleagues [71] indicate that PR significantly improves HRQoL in people with stable COPD. The pooled effects of PR on HRQoL, as measured by the SGRQ Total score (MD 6.9 points, 95% CI 9.3 to 4.5, n = 1146, moderate quality) and the CRQ dyspnoea score (MD 0.8 points, 95% CI, 0.6 to 1.0, n = 1283, moderate quality), were statistically significant and greater than the proposed MCIDs of 4 points and 0.5 points, respectively. Evidence was downgraded to moderate quality due to high levels of heterogeneity within the results. However, sensitivity analyses using trials with lower risk of bias yielded a similar estimate of the treatment effect, strengthening the validity of the findings that PR significantly improves HRQoL in people with COPD.

Few robust studies have evaluated the effects of combining education with exercise training in PR programs [71, 76]. Sub-group analyses performed within the Cochrane review by McCarthy and colleagues [71] showed no significant differences in improvements in SGRQ Total score (exercise only: MD -7.9 points, 95% CI -16.7 to 1.0, 5 trials; vs exercise and education: 6.8 points, 95% CI -9.2 to -4.3, 14 trials; $\chi^2 = 0.1$, $p = 0.8$) or CRQ dyspnoea score (exercise only: MD 0.8 points, 95% CI 0.6 to 1.1, 10 trials; vs exercises and education: MD 0.7 points, 95% CI 0.4 to 1.1, 9 trials; $\chi^2 = -0.3$, $p = 0.6$) when PR programs delivered exercise alone compared to exercise training combined with education. These results are supported by those from a large, high-quality randomised controlled trial conducted in Australia [76] which similarly found no benefit from the addition of education and individualised goal-setting to exercise training when compared to exercise training alone for improvements in CRQ dyspnoea score (MD -0.7 points, 95% CI -2.0 to 0.7, $p = 0.34$). However, the education component was delivered through group-based, didactic sessions; an approach that has been shown to be ineffective [59] and is not recommended [1, 23]. Likewise, in the Cochrane review by McCarthy, the subgroup analysis included trials with a mix of didactic, individualised and self-management education programs, making it challenging to determine whether the inclusion of individualised education or self-management interventions to PR improves HRQoL, and if so, which types are more effective.

Dyspnoea

As a prominent symptom reported by people with COPD, dyspnoea should be measured and reassessed as part of any PR program [6]. There are several scales

that can be used to evaluate dyspnoea in people with COPD [64, 83-85]. The visual analogue scale (VAS) [86] and Borg Dyspnoea scale [87] are the most common single-item scales used in PR to measure dyspnoea intensity and have been shown to be valid, reliable and responsive in people with COPD [88-91]. The modified Medical Research Council (mMRC) dyspnoea scale [91, 92] is another widely used tool to measure severity of dyspnoea according to different activity levels and can be used to predict hospitalisation rates [93] and prognosticate [93, 94] in people with COPD. However, the appropriateness of using the mMRC as a tool to detect meaningful change in dyspnoea following PR has been questioned [95]. Some multidimensional questionnaires, such as the CRQ [81] and SGRQ [80], can be used to assess dyspnoea amongst multiple other symptoms, with the CRQ producing a subdomain score for the impact of dyspnoea on HRQoL.

As detailed earlier, results from the Cochrane review by McCarthy and colleagues [71] demonstrated that PR significantly improves CRQ dyspnoea score when compared to usual care. Results from the Cochrane review [71] and a large randomised controlled trial by Blackstock and colleagues [76] suggest that there is no additional benefit from including education in PR programs for improvements in CRQ dyspnoea score. Likewise, Blackstock and colleagues [76] reported no significant difference in the proportion of participants who improved mMRC score by one point or greater (exercise only: $n = 28\%$; vs exercise and education: $n = 35\%$; $\chi^2 = 0.88$, $p = 0.35$). However, as discussed earlier, it remains unclear whether these results indicate that the addition of education to exercise training yields no additional benefits in reducing dyspnoea, or whether they were attributed to the inclusion of group-based, didactic education programs which have been shown to be ineffective in people with COPD [59]. Further research is required to determine the effectiveness of different approaches to education and self-management [96] and whether these can amplify the benefits in dyspnoea seen from exercise training alone.

Health status

The COPD assessment test (CAT) [97] is a relatively recent, disease-specific measure of health status that is simple and quick to complete [98], and strongly correlates with SGRQ [8, 98] and CRQ [99, 100]. The effects of PR on changes in health status in people with stable COPD were not examined in the Cochrane review

by McCarthy and colleagues [71]. Whilst there have been several observational studies that have examined the validity, reliability and responsiveness of the CAT to centre-based PR, which have been included in a systematic review [101], there has only been one randomised controlled trial [102] that has compared centre-based PR to standard care. The study has been published in Russian and there is minimal data presented in the abstract to interpret and critically appraise the findings. A recent randomised controlled trial [103] found no difference in CAT score between an eight-week (MD [standard deviation (SD)], baseline: 20 [6] points; vs eight weeks: 17 [7] points) and 12-week (MD [SD], baseline: 17 [6] points; vs 12 weeks: 15 [6] points) centre-based PR program, with both groups meeting the MCID of 2 points at program completion; however, whether this may have been achieved through standard care is not clear. Although there is a clear need for high-quality research evaluating the effects of centre-based PR on health status when compared to standard care, real-world audit data, published in the UK in 2019 [104], has indicated a potential effect of PR on improvements in health status. In 12,127 people with COPD, audit data showed that 56% of PR participants achieved the MCID of 2 points for CAT score. Other studies comparing centre-based PR to alternative PR models have reported changes in CAT scores and are discussed in detail later in this chapter.

Physical activity

The multi-dimensional nature of physical activity has led to the development of various physical activity measurement tools. Self-reported physical activity measures are important in understanding the experiences of people with COPD but cannot capture the intensity of physical activity [105]. Activity monitors are able to quantify physical activity and range in complexity from pedometers which are simple and inexpensive but may not be sensitive enough to detect change in people with COPD [106], to multi-axial accelerometers which detect acceleration in multiple axes but are more suited to measurements of physical activity levels in clinical trials [107].

Although changes in physical activity levels were not examined by McCarthy and colleagues [71], a Cochrane review by Burge and colleagues [108] evaluated 76 randomised controlled trials, which included a total of 8018 participants, that objectively measured changes in physical activity in people with COPD following physical activity interventions such as PR. Despite the limited evidence available, the

authors were able to perform a meta-analysis with three clinical trials and found that PR did not improve time in moderate to vigorous physical activity (MVPA) (MD 4 minutes [mins], 95% CI -2 to 9, n = 190, low quality) and daily step count (MD 208 steps, 95% CI -165 to 581, n = 180, low quality) compared to no intervention. However, when PR included high-intensity interval training, pooled results from two randomised controlled trials suggested a significant improvement in MVPA (MD 6 mins, 95% CI 4 to 8, n = 182, moderate quality). Similarly, a significant improvement in daily step count (MD 3174 steps, 95% CI 1453 to 4895, n = 33, moderate quality) was found following exercise training in one randomised controlled trial which combined exercise training with physical activity coaching and a pedometer compared to pedometer use alone. These findings suggest that additional physical activity interventions may need to be combined with PR to yield improvements in physical activity levels. However, the authors were unable to make strong conclusions due to the paucity of evidence available, and as a result, it remains unclear whether centre-based PR improves physical activity levels in people with COPD.

Self-efficacy

The concept of self-efficacy, introduced through Bandura's social cognitive theory [109], refers to an individual's belief in their ability to organise and execute the actions required for situations and tasks. Enhancing self-efficacy is recognised as a key factor in achieving behaviour change in people with COPD [64]. Questionnaires such as the General Self-Efficacy Scale (GSES) [110] and its PR-specific counterpart, the Pulmonary Rehabilitation Adaptation Index for Self-Efficacy (PRAISE) tool [111], measure confidence in managing a range of challenging or stressful situations. Other self-efficacy questionnaires target more specific domains, such as the COPD Self-Efficacy Scale (CSES) [112], which measures confidence in managing COPD-related breathing difficulties, or the Exercise Self-Regulatory Efficacy Scale (Ex-SRES) [113], which assesses confidence in maintaining regular exercise despite common COPD-related barriers. While the PRAISE [110, 114], CSES [115] and Ex-SRES [113, 116] have demonstrated good reliability and validity, only the CSES has shown responsiveness to PR [114, 115].

The effects of centre-based PR on self-efficacy remain unclear. A randomised controlled trial, published in 1984 by Atkins and colleagues [117] compared three

exercise groups incorporating either behaviour modification, cognitive-behaviour modification or cognitive modification to an attention control and a no-treatment control. The exercise groups demonstrated significantly greater improvements in walking efficacy judgment, measured using a custom-designed tool adapted from Bandura's theory [109], compared to the attention control group. Another randomised controlled trial by Gormley and colleagues [118] compared exercise programs with or without coaching and found no significant difference in exercise confidence scores. While these findings [117, 118] suggest that exercise may play a key role in improving self-efficacy, the self-efficacy measurement tools used in these trials were unidimensional and lacked formal validation, limiting the strength and generalisability of the conclusions. Further research is necessary to determine whether centre-based PR improves self-efficacy and to identify which specific components of the program may most effectively promote self-efficacy in people with COPD.

In summary, a large and comprehensive Cochrane review by McCarthy and colleagues [71] demonstrated that there was moderate to low quality evidence that centre-based PR is effective for people with stable COPD in improving exercise capacity, HRQoL and dyspnoea. However, there are a lack of randomised controlled trials to determine whether centre-based PR improves health status, physical activity levels and self-efficacy in people with stable COPD when compared to standard care. The inclusion of education to a PR program appears to offer no additional benefit for improvements in exercise capacity, HRQoL and dyspnoea [71, 76], yet there is a recognised need for further high-quality research to evaluate the effectiveness of different educational approaches and self-management interventions provided to a PR population [96]. Clinical practice guidelines [1, 3, 4, 119] have drawn on the findings from McCarthy and colleagues [71] to strongly recommend that people with stable COPD participate in PR programs. McCarthy and colleagues [71] concluded that further research comparing PR to standard care were no longer warranted. Although considering the large heterogeneity in regard to PR program characteristics, the authors recommended that future research should evaluate the effects of certain program characteristics, such as program delivery mode, program components and degree of supervision [71].

Economic impacts

To interpret the evidence on the health outcomes and consequences of delivering PR to people with COPD, it is crucial to understand the key components of an economic evaluation. Depending on the type and comprehensiveness of the economic analysis chosen, results may represent an analysis of health outcomes (e.g. HRQoL) and/or monetary costs [120]. Full economic evaluations measure the costs and health outcomes for an intervention(s) and a comparator [120]. The measurement of costs between studies will vary depending on the perspective taken in the economic analysis. A special task force from the International Society for Pharmacoeconomics and Outcomes Research recommended that economic evaluations in healthcare should present both costs from a healthcare sector perspective and a societal perspective [121]. Healthcare sector costs include direct medical costs paid by the patient and the healthcare provider [122]. Whereas a societal perspective can include costs associated with direct medical costs (e.g. consumption of resources to provide an intervention and healthcare utilisation as a consequence of an intervention), direct non-medical costs incurred by patients (e.g. travel), labour productivity costs or losses (e.g. employment overheads or time missed from paid employment), and non-health sector costs (e.g. education, housing and justice system) [122].

Hospitalisation costs are the primary contributor to the high economic impact of COPD [123]. The delivery of PR to people with stable COPD [3] and following an exacerbation of COPD [72, 124] significantly reduces healthcare utilisation and suggests that centre-based PR could be cost-effective [125]. Several economic evaluations [126-134] of centre-based PR have been conducted, varying in study design, including randomised controlled trials [127, 129], quasi-experimental [132] or cohort studies [128], simulation models [126, 130, 133, 134] and an economic impact assessment [131]. Findings have demonstrated that centre-based PR is cost-effective [126, 129-131, 133, 134] and cost-saving [127, 130, 131] when compared to standard care. However, due to the considerable heterogeneity in study design, input parameters, time horizons, base year and currency, comparing the values reported in the studies is limited. One simulation model found that centre-based PR would be considered cost-saving up to \$171 USD (\$313 calculated in 2024 AUD when adjusting for currency conversion [135] and inflation [136]) per participant per

session. A lower cost-saving threshold [131] of 1,545 British Pounds (£) (\$3159 calculated in 2024 AUD when adjusting for currency conversion [135] and inflation [136]) per participant per program was estimated for a hypothetical centre-based PR program in the United Kingdom (UK). These costs have been converted to 2024 AUD to allow for comparisons to be made with the findings reported in Chapter 4. The range of values in the findings from these economic evaluations highlight how variations in global healthcare systems can limit the generalisability of results across different countries. However, these cost-saving thresholds allow estimations of the resource costs that could be deployed when delivering a PR program and potential cost-savings. In the subsequent sections of this chapter, focus will be directed to evaluating the costs associated with resources used in various PR models to align with the findings of the cost-analysis reported in Chapter 4.

The resource usage costs to deliver centre-based PR programs have been reported in 12 studies [128, 129, 132, 137-145] and varied significantly due to differences in program components, frequency, duration and country. In an Australian context, the resource usage costs of delivering centre-based PR have been estimated to be between \$292 and \$529 [142-144] (\$430 to \$632 calculated in 2024 AUD when taking into consideration inflation [136]). In studies that measured actual costs [128, 132, 140-145] for delivering centre-based PR, as opposed to considering national reimbursement rates [137, 138], the costs associated with staff wages were responsible for the majority of the resource usage costs. Hence, centre-based PR program costs will rise in programs with greater frequency of supervised sessions, longer program durations and/or in countries with higher staff wages. The significant contribution of staff wages to the resource usage costs of centre-based PR programs highlights the need for future studies to evaluate the clinical effectiveness and cost-effectiveness of programs that require less staff supervision.

Environmental impacts

Only one study has included a limited analysis of the environmental impact of centre-based PR. A quasi-experimental study [132] reported the cost of pollution associated with participant car travel as €24.2 (\$43 calculated in 2024 AUD when adjusting for currency conversion [135] and inflation [136]) per participant. The validity and accuracy of this finding is unclear as the methods used to measure participant car travel and pollution levels were not described and GHG emissions from other

components of centre-based PR were not taken into account. Reporting air pollution as a cost limits the ability to decipher actual impacts on the environment. Further research is required to determine the carbon footprint of centre-based PR and should follow methods commonly used by healthcare organisations.

The GHG Protocol [146, 147] is a set of internationally accepted accounting tools to quantify the carbon footprint of organisations and governments, and are useful in determining the direct and indirect GHG emissions from healthcare systems and programs. The GHG protocol categorises GHG emissions into three scopes. Scope 1 emissions refer to any GHG emissions that occur as a direct result of an activity within the organisation's control. Examples include the combustion of fuels for vehicle use and the use of anaesthetic gases. Indirect GHG emissions from the generation of electricity that is consumed by an organisation are considered as Scope 2 emissions. Scope 3 emissions are all other indirect GHG emissions other than those associated with electricity use. Scope 3 emissions in healthcare can include the GHG emissions generated by the manufacturer of medical equipment and consumables, staff commutes, patient and visitor travel, and waste disposal [148]. Upstream scope 3 emissions include any indirect GHG emissions associated with the production of goods and services that are used by the organisation. Downstream scope 3 emissions are any indirect GHG emissions generated from the use of a product or service that was sold or provided by the organisation. Scope 1, 2 and 3 emissions that may be associated with a centre-based PR program are summarised in Figure 1.3 and should be accounted for in future research. The study in Chapter 4 demonstrates the classification of GHG emissions as Scope 1, 2 and 3 emissions when evaluating the carbon footprint of PR programs.

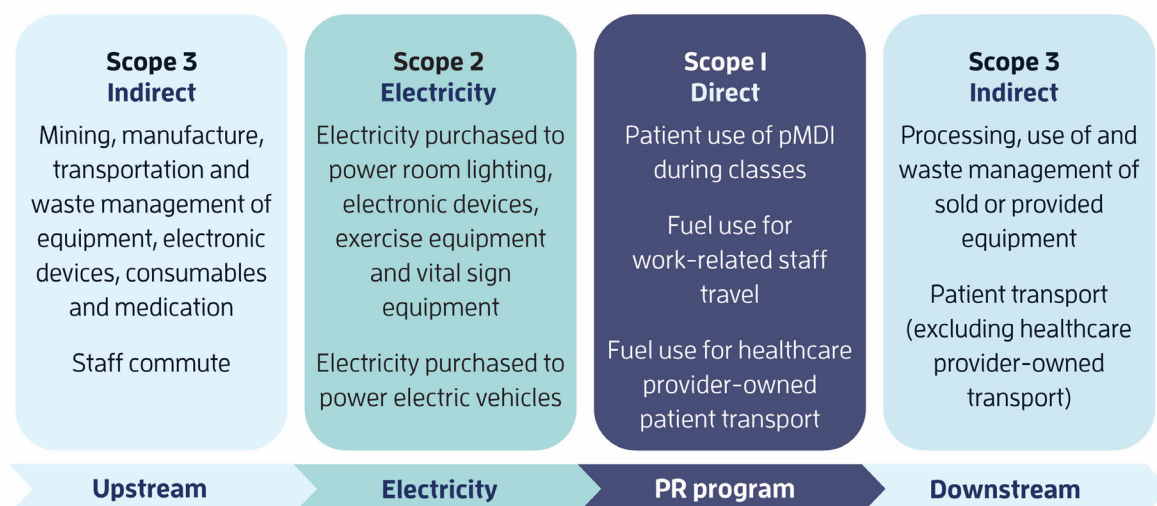


Figure 1.3. Carbon footprint components of centre-based PR. Scope 1 (direct GHG emissions), Scope 2 (indirect GHG emissions for purchased electricity) and Scope 3 (all indirect GHG emissions other than for purchased electricity) emissions associated with the delivery of centre-based PR. Upstream Scope 3 emissions are associated with the production of goods and services that are used by the healthcare provider. Downstream Scope 3 emissions are associated with indirect GHG emissions from the use of a product or service that is sold by the healthcare provider. GHG: greenhouse gas; pMDI: pressurised metered-dose inhaler.

Facilitators and barriers to pulmonary rehabilitation

Access and uptake

Despite the clear benefits of centre-based PR for people with COPD [3, 4, 71, 124], significant challenges remain with access to and uptake of the program [4-6]. Access to centre-based PR programs is not widely available across jurisdictions [149], with programs not operating at all in some low- and middle-income countries [150, 151]. When centre-based PR programs are available, healthcare professionals refer only 3% to 30% [13, 152, 153] of people with COPD eligible for PR, creating an additional barrier to PR access. The infrastructure and capacity of a PR program influences whether a PR service can accept referrals and assess potential participants in a timely manner [4, 6, 154]. Significant delays in commencing PR following receipt of referral have been reported globally [75, 155, 156]. The demand for PR in Australia is expected to increase as the Australian Commission on Safety and Quality in Health Care Clinical Care Standards [157] are implemented, with one standard calling for the referral of people with COPD to PR. National strategies to increase the capacity of PR services, such as PR models that require less resources and staff time [5], need to be explored to be able to meet this demand.

Even when referrals are made, the uptake of centre-based PR among people with COPD remains low [152, 158-160]. Thirty percent of people with COPD referred to centre-based PR in the UK do not accept the offer of PR [152, 153]. In other countries such as the USA [158] and New Zealand [159], uptake rates have been found to be as low as 4% and 1%, respectively. Participant beliefs and expectations, such as the lack of perceived benefits of PR and fear that exercise would exacerbate health conditions, strongly influence PR uptake [161, 162]. An ATS policy statement [5] highlights the importance of educating people with COPD on the benefits of PR and addressing misconceptions. Other important areas to target include challenges with travel, transport and PR location that are significant barriers to centre-based PR uptake [162, 163] and attendance [161]. Geographical distances to PR sites can vary significantly between countries, with longer travel distances a predictor of non-attendance [161, 164] and non-completion [165]. People in regional, rural and remote areas of Australia need to travel greater distances to access health care [166, 167]. Interventions that allow people with COPD to complete PR programs at home are recommended to overcome these barriers [5, 155] and are examined in the subsequent section of this chapter.

Adherence and completion

An international survey [14] of healthcare professionals reported a high median PR completion rate of 75% to 90% in people with COPD. However, completion rates found in clinical practice have been lower, ranging from 56% to 73% [152, 168]. Completion and adherence terminology have been used throughout PR clinical trials; however, there is a distinct difference between the two. Completion rates can simply represent attendance to a discharge assessment [6], whereas adherence, defined as the extent at which an individual's behaviour corresponds with the agreed recommendations from a healthcare professional [169], provides a clearer picture of how well people with COPD engage in a PR program to set targets. Adherence to evidence-based interventions is needed for people to achieve the benefits of PR reported in the literature [169]. As discussed earlier in this chapter, exercise training significantly improves exercise capacity and HRQoL in people with COPD [71]. As such, adherence can be measured when participants attend a certain pre-determined proportion of exercise sessions [170, 171]. Recent clinical trials using adherence thresholds of 70% to 85% of exercise sessions attended have reported

centre-based PR adherence rates that varied greatly between 49% and 79% [103, 172-176]. In-depth measurements of adherence to the prescribed frequency, intensity, time and/or type of exercise may provide greater insights into the likelihood of benefiting from PR in people with COPD and are discussed further in Chapter 3.

Despite strong evidence supporting the benefits of PR, fewer than 10% of Australians with COPD have participated in a program [177]. Participation rates may be even lower in regional, rural and remote communities where COPD prevalence is higher [28] and access to PR programs is limited [178]. To improve access and uptake, there is a pressing need to explore alternative models of PR delivery that improve or maintain current levels of adherence and completion.

Effects of home-based pulmonary rehabilitation

Effects on clinical outcomes

Home-based PR may be an effective option to improve clinical outcomes in people with COPD whilst overcoming some of the barriers for access to and uptake of centre-based PR [6, 64, 155]. The delivery of supervised or unsupervised exercises in the home environment could resolve difficulties experienced by people with COPD, such as those associated with transport, travel and PR location [155], without the need for additional centre-based PR space. Zheng and colleagues [179] presented an overview of 11 systematic reviews of home-based PR in people with mild to very severe COPD, with participant numbers ranging from 464 to 2352. Most of the included reviews indicated that home-based PR was superior to standard care, and non-inferior to centre-based PR for improvements in exercise capacity, HRQoL and dyspnoea. Although the authors [179] were able to determine that home-based PR was safe due to the absence of adverse events, firm conclusions regarding the clinical efficacy of home-based PR were not possible as the quality of the included systematic reviews were low or very low. In addition, there were high levels of bias and heterogeneity in the studies included in the systematic reviews in terms of program structure and level of supervision provided.

A systematic review with meta-analysis [180] that evaluated the effects of home-based PR on clinical outcomes when compared to standard care or centre-based PR has since been published. Sixteen randomised controlled trials collectively included a total of 1,800 participants with a range of COPD severities. Sub-group meta-

analyses were performed of trials that used the same outcome measure and findings supported those reported by Zheng and colleagues. [179], with home-based PR significantly improving 6MWD by 62 m (95% CI 46 to 77, $p < 0.001$, 4 studies, $n = 107$) and SGRQ Total by -6 points (95% CI -8 to -3, $p < 0.001$, 3 studies, $n = 83$) when compared to standard care. Sub-group analyses also determined home-based PR to be no different to centre-based PR for improvements in exercise capacity (MD -6 m, 95% CI -19 to 6, $p = 0.32$, $n = 411$) and the CRQ Dyspnoea domain (MD -0.1 points, 95% CI -0.5 to 0.3, $p = 0.64$, $n = 379$), and superior for improvements in CAT score (MD -1.5 points, 95% CI -2.8 to -0.2, $p = 0.02$, $n = 163$). Although the grouped sample sizes were smaller, there was little to no heterogeneity found in the sub-group analyses, increasing the certainty with the results.

Neither systematic review [179, 180] examined the effects of home-based PR on physical activity levels. High quality randomised controlled trials [175, 181, 182] have found inconsistent results for the effect of home-based PR on changes in physical activity levels in people with COPD. One high-quality randomised controlled trial [181] compared home-based PR to standard care and found statistically significant improvements in low-intensity (MD 19 mins, 95% CI 5 to 33) and total physical activity (MD 26 mins, 95% CI 7 to 45), but not moderate-intensity physical activity (MD 7 mins, 95% CI -1 to 15), following home-based PR. When compared to centre-based PR, two high-quality randomised controlled trials [175, 183] reported conflicting results, with one trial [182] finding a statistically and clinically significant improvement in daily step count (MD 1463 steps, 280 to 2645) favouring home-based PR, and the other [175] finding no between-group (MD 680 steps, 95% CI -286 to 1648) or within-group differences in either the home-based or centre-based PR groups. However, in the trial that found superiority, a substantially high attrition rate occurred, with only 33% of the participants included in the analysis, which significantly limited the validity of the results. The home-based PR programs did not include any additional physical activity intervention in addition to an exercise program, and similar to centre-based PR, there may be a need to integrate additional interventions, such as the use of pedometers and health coaching, for home-based PR to successfully improve physical activity levels in people with COPD.

The effectiveness of home-based PR on self-efficacy, compared to centre-based PR, has been evaluated in two randomised controlled trials [175, 183]. Only one trial

[183], conducted by Horton and colleagues, reported a significant between-group difference in PRAISE score in favour of centre-based PR (MD -2.6 points, 95% CI -4.9 to -0.3, $p = 0.03$). However, these results were derived from a complete case analysis, with high dropout rates in both the home-based PR ($n = 35\%$) and centre-based PR ($n = 41\%$) groups, limiting the reliability of the results due to potential bias. In contrast, an intention-to-treat analysis performed by Holland and colleagues [175] found no significant within-group or between-group differences in PRAISE scores when comparing home-based PR and centre-based PR programs (MD 1.3 points, 95% CI -1.2 to 3.7, $p > 0.05$), suggesting either that PR, regardless of delivery mode, may not significantly improve self-efficacy, or that the PRAISE tool lacks sensitivity to detect such changes.

Overall, there was low to moderate quality evidence that home-based PR is safe and superior to standard care, and equivalent to centre-based PR, for improvements in exercise capacity and HRQoL. There is also some evidence to suggest that people with COPD may benefit more from home-based PR than centre-based PR for improvements in health status. Further research is needed to allow for stronger conclusions to be made and to determine whether the addition of physical activity interventions to home-based PR programs can yield positive results on physical activity levels.

Economic impact

Economic evaluations of home-based PR have been conducted in two randomised controlled trials [143, 184]. A feasibility two by two factorial trial [184] compared the direct medical costs to the healthcare provider for two-weeks of inpatient PR, supervised home-based PR, a combination of the two and standard care in 2018 in the UK. Intervention costs accounted for equipment (hospital group only) and staff time for delivering the intervention and travel for home-visits. The resource usage costs to deliver PR were higher for the home-based PR program (£209 per program; \$525 calculated in 2024 AUD after adjusting for currency conversion [135] and inflation [136]) than the hospital PR program (£103 per program; \$259 calculated in 2024 AUD after adjusting for currency conversion [135] and inflation [136]) due to additional staff time required for travel to and from participants' homes. In contrast, the resource usage costs of an eight-week unsupervised home-based PR program (\$327 in 2017 AUD) in Australia [143] were similar to a centre-based PR (\$345 in

2017 AUD) (home-based PR: \$407, vs centre-based PR: \$430 calculated in 2024 AUD after adjusting for inflation [136]) and the programs were equally as cost-effective. In both randomised controlled trials [143, 184], staffing wages accounted for most of the PR program costs and suggest that healthcare provider costs for resources used to deliver home-based PR may be minimised when delivering an unsupervised home-based PR session that requires less staff time. Neither trial [143, 184] accounted for costs incurred by participants to complete the PR sessions, although one trial [143] evaluated direct medical costs from accessing medical care and medications and found no difference between home-based PR and centre-based PR. Participant travel avoidance in the home-based PR group was not accounted for in either trial, potentially underestimating the cost-savings and should be evaluated in future studies.

Environmental impact

To date, there have been no published studies investigating the environmental impact of home-based PR when compared to standard care or to centre-based PR. Home-based PR eliminates the requirement for people with COPD to travel to and from PR sites for exercise sessions and as such, there may be a reduction in GHG emissions associated with home-based PR, but this has yet to be confirmed in the literature.

Adherence

Although found to be as safe as centre-based PR [179], there have been concerns raised around participant adherence to home-based PR programs when exercise sessions are unsupervised [185, 186]. On the contrary, a systematic review [180] identified three studies [173, 175, 187] evaluating home-based PR, two of which included unsupervised exercise sessions, and found that adherence rates to home-based PR ranged from 73% to 98% which was higher than adherence rates for the corresponding centre-based PR programs, ranging from 49% to 93%. Weekly telephone calls [175], a paper-based exercise diary [187] and videoconferencing calls [173] were employed in lieu of direct face-to-face supervision and highlight the potential for remote supervision to optimise adherence. The evolution and growing accessibility of digital technologies has presented new opportunities to provide remote supervision and enhance the comprehensiveness of home-based PR programs and are explored in the next section.

TELEREHABILITATION FOR THE DELIVERY OF PULMONARY REHABILITATION IN PEOPLE WITH COPD

Definitions

Telerehabilitation pulmonary rehabilitation

Telerehabilitation involves the use of digital technologies to support the remote delivery of rehabilitation programs [188]. Innovations in digital technologies have rapidly increased since the invention of the microchip in 1958 that allowed manual processes to transition to digital ones. Digital technologies such as smartphones, tablet devices and personal computers are integral to daily life and have generated growing interest in the use of technologies to provide alternative models of PR for those who are unable to access centre-based PR [4, 23, 64, 74]. Telerehabilitation can be employed to deliver long-term maintenance exercise programs, physical activity interventions and PR programs, with the former two being beyond the scope of this literature review. Telerehabilitation is most commonly used to deliver PR in the home but can also be used to optimise rehabilitation programs within healthcare facilities or in the community [6, 189]. Some form of bi-directional interaction between participants and healthcare professionals is required [6]. The use of tele-monitoring equipment alone in addition to home-based PR should therefore not be considered telerehabilitation and can be referred to as tele-monitoring PR [190]. Communication between participants and healthcare providers may be in real-time through telephone or videoconferencing calls, or through delayed messaging such as text messages, electronic mail or online chat through a web-based portal or mobile app.

Videoconferencing pulmonary rehabilitation

Telerehabilitation PR delivered through videoconferencing platforms (videoconferencing PR) facilitate the remote supervision of home-based PR by enabling people with COPD and healthcare professionals to communicate through real-time audio and video calls. Videoconferencing platforms typically allow multiple users and therefore can facilitate group-based exercise and education classes with a healthcare professional. A systematic review [191] of 32 telerehabilitation PR studies identified videoconferencing platforms as the most common type of digital technology used. Videoconferencing PR studies have typically provided participants

with an array of equipment [192] and require internet connection to facilitate the technology.

Web-based pulmonary rehabilitation

Web-based PR refers to telerehabilitation PR programs that are supported by web-based platforms other than videoconferencing platforms. Web-based platforms are accessed through a web-browser and can be used on various electronic devices with internet access such as smartphones, tablet devices and personal computers. A range of modules can be delivered through the web-based platforms and independently completed by people with COPD [6]. These modules can include, but are not limited to, education topics, symptom questionnaires and exercise programs [192]. Exercise programs are typically performed at home without supervision [193-196], with healthcare professionals prescribing, monitoring and progressing programs remotely through the web-based platform [197].

Mobile health pulmonary rehabilitation

Mobile health (mHealth) refers to the use of mobile devices, such as smartphones and tablet devices, to support public health practice [198]. Smartphone technology originated in 1992 with the development of the IBM Simon Personal Communicator (IBM, Armonk, New York, USA) that featured a touchscreen, telephone capabilities and basic smartphone apps. Since then, smartphone technology usage has experienced rapid growth, with approximately 80% of the global population and 95% of the population in high-income countries owning a smartphone [15]. The number of people with smartphone subscriptions now surpasses the number with access to basic infrastructure such as paved roads, electricity and fixed internet in low- and middle-income countries [199]. Combined with the potential to improve access to health care, this has made mHealth a focus area of development by the World Health Organisation [200].

The integration of mHealth into the delivery of PR can take on many forms and can include the telerehabilitation PR models previously mentioned, such as home-based PR supported by telephone calls, and web-based and videoconferencing platforms accessed through a smartphone or tablet device. mHealth apps offer an additional avenue for delivery, differing from web-based PR by requiring the download and installation of specific apps on smartphone or tablet devices. mHealth apps are built

on specific operating systems (OS), such as iPhone OS (iOS) (Apple Inc. Cupertino, California, USA) and Android OS (Google LLC, Mountain View, California, USA), and as such will often provide better offline capabilities and therefore, may be better suited for people in Australia who live in regional, rural and remote communities where there are limitations to broadband and mobile connectivity [201].

There is considerable crossover between the definitions of home-based PR, tele-monitoring PR, videoconferencing PR, web-based PR and mHealth PR, leading to discrepancies in how they are evaluated in the literature [6, 191, 192, 197]. Bonnevie and colleagues [202] published a letter to the editor in 2021 suggesting a framework for defining home-based PR and telerehabilitation PR against a continuum of technological requirements. Although this framework clearly compares the technological requirements for home-based PR and telerehabilitation PR, it does not integrate well with other definitions described in the literature. A recent ATS workshop report has identified the differences between home-based PR, telerehabilitation PR and web-based PR [6], but does not include a definition for mHealth PR. A combined approach of the two, as summarised in Figure 1.4, would distinguish between the technology types and reflect language that is evolving in the literature. As such, mHealth PR will be defined in this manuscript as the use of apps on mobile devices, such as smartphone or tablet devices, to facilitate PR in the home environment.

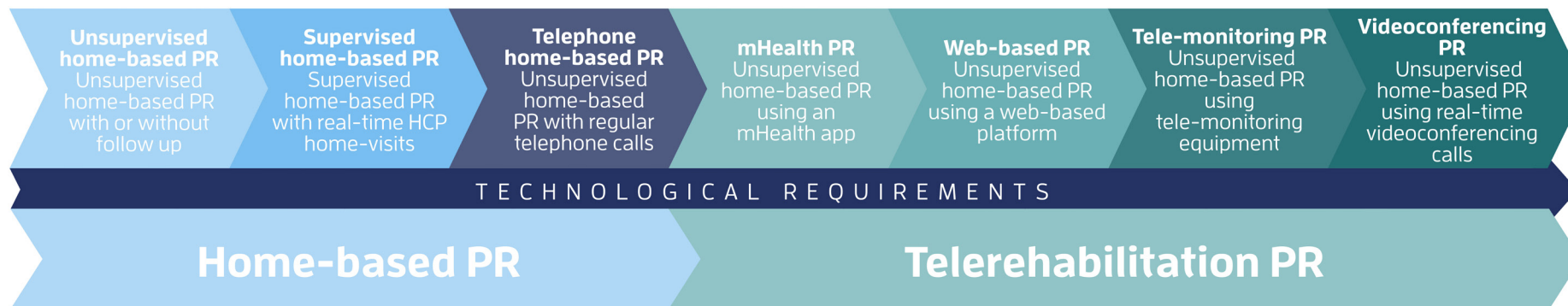


Figure 1.4. Terminology for home-based PR and telerehabilitation PR. Types of home-based PR and telerehabilitation PR on a continuum of increasing technological requirements. Home-based PR includes unsupervised home-based PR, supervised home-based PR and telephone home-based PR. Telerehabilitation PR includes mHealth PR, web-based PR, tele-monitoring PR and videoconferencing PR. (Adapted from *Urgent need to define telerehabilitation for respiratory disease* [202] and *Defining Modern Pulmonary Rehabilitation. An Official American Thoracic Society Workshop Report* [6]).

App: application; HCP: healthcare professional; mHealth: mobile health; PR: pulmonary rehabilitation

Effects of videoconferencing pulmonary rehabilitation

There are numerous systematic reviews [191, 197, 203-207], meta-analyses [4, 191, 197, 203-205] and a Cochrane review [188] that have examined the effects of telerehabilitation PR in people with COPD. Results from these studies have deemed telerehabilitation to be at least non-inferior to centre-based PR for improvements in exercise capacity [4, 188, 191, 197, 203-207], HRQoL [4, 188, 197, 203-205, 207], health status [188, 191, 205], physical activity [188, 191, 204, 207], dyspnoea [4, 188, 191, 203-205], anxiety and depression [205, 206], and safety [4, 207]. There was considerable heterogeneity in the 55 studies included in these reviews in regard to the mode of telerehabilitation PR and the structure of the exercise program, making it difficult to interpret the specific effects of each telerehabilitation PR modality. Consequently, only the randomised controlled trials [172, 173, 208] comparing videoconferencing PR to standard care [208] and centre-based PR [172, 173] have been chosen to discuss the effects of videoconferencing PR on clinical outcomes in the subsequent sections (summarised in Appendix 1). The randomised controlled trials were of high quality and examined people with mild to very severe COPD. Participants were either not required to have experience with technology [172, 173] or at least operate a computer independently with training [208]. The trial by Cox and colleagues [172] recruited people with other chronic respiratory diseases, but the majority of participants (70%) were people with COPD and therefore, has been included in the subsequent sections. Videoconferencing PR programs [172, 173, 208] included most of the essential components of PR [6], delivering similar programs of two to three, group-based videoconferencing exercise sessions per week for eight to ten weeks, allowing for a comparison of findings.

Exercise capacity

The effects of videoconferencing PR on improvements in exercise capacity in people with COPD were investigated in the three randomised controlled trials [172, 173, 208]. Tsai and colleagues [208] reported that exercise capacity, as measured by the ESWT, was significantly greater (MD 360 seconds [s], 95% CI 153 to 526, $p = 0.001$) when compared to standard care. These improvements were clinically significant, surpassing the proposed MCID for the ESWT of 180 s. However, no statistically significant improvement was seen when measuring exercise capacity using the 6MWD (MD 45 m, 95% CI -18 to 108, $p = 0.16$) or the ISWT (MD 6 m, 95% CI -23 to

35, $p = 0.66$). The wide confidence intervals around the MDs in the 6MWD and ISWT were likely related to the relatively low sample size ($n = 36$), powered for change in ESWT, which subsequently lowered the certainty of these results.

Two randomised controlled trials [172, 173] similarly found no differences between videoconferencing PR and centre-based PR for improvements in exercise capacity when measured using the 6MWD (Hansen [173]: MD 6 m, 95 CI -23 to 10; Cox [172]: MD -6 m, 95% CI -26 to 15). Within-group differences in exercise capacity significantly improved by 17 m (95% CI 6 to 29) [173] to 23 m (95% CI 10 to 36) [172] following videoconferencing PR, but did not reach the proposed MCIDs of 26 m [173] to 30 m [172]. Interestingly, the centre-based PR programs likewise did not reach clinical significance (Hansen [173]: MD 24m, 95% CI 12 to 35; Cox [172]: MD 25 m, 95 CI 11 to 40). The frequency and duration of supervised exercise sessions in these studies [172, 173] were less than those recommended by PR official statements [64, 209] and may explain the lack of clinical significance with these findings.

Although few high-quality randomised controlled trials [172, 173, 208] exist, the findings suggest that videoconferencing PR is more effective than standard care and no different to centre-based PR for improvements in exercise capacity in people with COPD. Further research is needed to determine whether clinically meaningful improvements in exercise capacity can be achieved when delivering videoconferencing PR programs that meet recommendations for PR exercise training.

Health-related quality of life

In the three randomised controlled trials [172, 173, 208], videoconferencing PR did not result in significant differences in HRQoL when compared to standard care (CRQ Total: MD 8 points, 95% CI -1 to 16) [208] or centre-based PR (Hansen [173]: COPD Clinical Questionnaire [CCQ] MD -0.3 points, 95% CI -0.4 to -0.1; Cox [172]: CRQ Total MD 9.1 points, 95% CI 3.5 to 14.8). Although videoconferencing PR programs resulted in statistically significant within-group improvements in HRQoL, these results were not clinically significant. This was despite all trials delivering a comprehensive videoconferencing PR program with [172, 173] or without [208] education. The randomised controlled trials were not powered to detect change in

HRQoL which may account for the lack of clinically significant findings. While it appears that videoconferencing PR does have some positive impact on HRQoL in people with COPD, further high-quality research is needed to determine which components of the program may be adapted or enhanced to yield clinically relevant results.

Dyspnoea

Tsai and colleagues [208] demonstrated that videoconferencing PR did not significantly improve dyspnoea, measured using the CRQ dyspnoea score, when compared to standard care (MD 2.8 points, 95% CI -0.5 to 6.1). Similarly, in the randomised controlled trial by Cox and colleagues [172], videoconferencing PR did not significantly improve CRQ dyspnoea score (MD -1.0 points, 95% CI -3.3 to 1.2) or mMRC score (MD 0 points, 95% -0.3 to 0.3) when compared to centre-based PR. However, both the videoconferencing PR (MD 3.9 points, 95% CI 2.4 to 5.4) and centre-based PR (MD 4.6 points, 95% CI 2.7 to 6.5) groups achieved clinically and statistically significant within-group improvements in the primary outcome measure, CRQ dyspnoea score. In contrast, the videoconferencing PR program evaluated by Tsai and colleagues [208] did not achieve clinically or statistically significant changes in CRQ dyspnoea score (MD 2.2 points, 95% CI -0.1 to 4), despite significant gains in exercise capacity. This may be attributed to the trial being underpowered to detect change in CRQ dyspnoea score, or possibly due to the absence of education and self-management interventions, which were key components of the PR programs in the trial by Cox and colleagues [172].

Health status

Tsai and colleagues [208] found that videoconferencing PR trended towards statistical significance for improvements in the CAT score (MD -3 points, 95% CI -7 to 0) when compared to standard care. Although Hansen and colleagues [173] reported no significant difference in CAT score (MD -1.4 points, 95% CI -3.0 to 0.1) with videoconferencing PR and centre-based PR, when adjusted for differences in baseline characteristics, videoconferencing PR yielded statistically significant improvements in the CAT score with a MD of 1.6 points (95% CI 0.1 to 3.3) when compared to centre-based PR; however, this did not reach clinical significance. Similar findings [180] have been reported when comparing home-based PR to

centre-based PR and suggests there may be a favourable effect on health status in people with COPD when performing exercises in the home environment.

Physical activity

The videoconferencing PR program evaluated by Tsai and colleagues [208] was equally as ineffective than standard care for improving physical activity levels when measured using a tri-axial accelerometer (daily steps MD 475 steps, 95% CI -200 to 1151). When compared to centre-based PR in two randomised controlled trials [172, 173], videoconferencing PR was considered equivalent for changes in physical activity levels. Tri-axial accelerometers were used to measure physical activity in these trials [172, 173], but one trial [173] reported daily step count (MD -283 steps, 95% CI -845 to 278) and the other [172] light intensity physical activity (MD -22 mins, 95% CI -61 to 17) and MVPA (MD -2 mins, 95% CI -18 to 14), and therefore, comparing the mean differences was not possible. Within-group changes were not statistically significant, with the exception for one centre-based PR group [173] which significantly worsened daily step count (MD -400 steps, 95% CI -803 to -2). These findings suggest that videoconferencing PR is equally as ineffective on improving physical activity levels as centre-based PR.

Self-efficacy

The effects of videoconferencing PR on self-efficacy remain inconclusive. Tsai and colleagues [208] demonstrated that an eight-week videoconferencing PR program, delivered without an education component, significantly improved self-efficacy as measured by the PRAISE score (MD 8 points, 95% CI 2 to 14 points) compared to standard care. Conversely, Cox and colleagues [172] reported no significant change in PRAISE scores following either an eight-week videoconferencing PR or a centre-based PR program (MD 1 point, 95% CI -1 to 3). Notably, the lack of effect occurred despite high engagement with the structured group-based and individualised education and self-management interventions, and participants generally expressed confidence in using technology. As previously discussed, the videoconferencing PR program evaluated by Cox and colleagues [172] did not yield clinically meaningful improvements in exercise capacity, whereas the program delivered by Tsai and colleagues [208] did. This discrepancy may suggest a potential association between improvements in exercise capacity and self-efficacy. However, given neither trial was powered to detect change in PRAISE score and the variability in program design,

further research, specifically trials that assess self-efficacy as a primary outcome, is warranted.

Adverse events

Reassuringly, there were no serious adverse events reported in any of the videoconferencing randomised controlled trials [172, 173, 208]. Only two adverse events were reported in a single trial [173] that were related to minor musculoskeletal pain from exercises and occurred solely in the centre-based PR program. These findings suggest that PR can be delivered safely to people with COPD in the home when exercises are remotely supervised through videoconferencing platforms.

Technological issues

While complications arising from the use of technology are not categorised as adverse events, they remain important considerations in the implementation of videoconferencing PR programs. Technological issues, such as poor internet connection, were reported in 12% [208] to 14% [173] of videoconferencing sessions. In one study [172], a significant proportion of participants (n = 42%) required additional support to use the technology equipment or resolve technological issues. In part, this can be explained by participants not needing to have prior experience with computers or the internet to be included in the study. The configuration of the telerehabilitation equipment in all three studies did not accurately reflect typical use of personal technology devices. Tablet devices or laptop computers were mounted on stands to allow staff to visually and verbally communicate to participants whilst exercising [172, 173, 208], and unfamiliarity with this technology and set-up, and low baseline technology skills may have limited the ability of participants to seamlessly use the technology without assistance. Technology skills and experience with various digital technologies should be considered when delivering videoconferencing PR in people with COPD.

Engagement

To date, only one randomised controlled trial [172] has evaluated participant engagement to videoconferencing PR when compared to centre-based PR. Results showed that participants in the videoconferencing PR group were more engaged (97%) with the videoconferencing education sessions than participants in the centre-based PR group were with the face-to-face education sessions (84%, $p = 0.009$).

However, this high overall engagement was not maintained across the 30 education topics, as participants engaged with only a median of three education topics (interquartile range [IQR], videoconferencing PR: 2 to 4; centre-based PR: 2 to 5), with the majority of the participants engaging with the education sessions that discussed how to manage an exacerbation of COPD and ongoing exercise participation. The findings show that people with COPD can be as highly engaged with remotely delivered education sessions as to face-to-face sessions; however, this may only be limited to three education topics. Future studies are needed to determine whether this is consistent across other videoconferencing PR programs.

Adherence

Adherence to the videoconferencing PR exercise sessions was high across the three randomised controlled trials [172, 173, 208], ranging between 73% and 92%. When considering attendance to at least 70% of exercise sessions, adherence was similarly high between videoconferencing PR (73% to 84%) and centre-based PR (63% to 79%) [172, 173], and demonstrates that adherence is not affected by remote supervision of exercises. Hansen and colleagues [173] demonstrated that the odds of PR completion was three times greater (odds ratio [OR] 3.18, 95% CI 1.37 to 7.35, $p < 0.01$) for videoconferencing PR than for centre-based PR. Participants in this study had severe to very severe COPD and multi-morbid conditions, with 34% reliant on a walking aid for mobility, and as a result, may have represented a cohort who had greater difficulties accessing centre-based PR sites for regular exercise sessions. Eliminating the need to travel to and from PR sites by delivering videoconferencing programs in the home environment may explain the greater completion rates and presents a clear advantage over centre-based PR.

Economic and environmental impact

To date, only two secondary analyses [144, 210] of the same randomised controlled trial [172] have evaluated the economic [144] and environmental [210] impacts of videoconferencing PR in Australia. Although videoconferencing PR was found to be as cost-effective as centre-based PR [144], results from the economic analysis [144] found that participant resource usage costs were lower for those in the videoconferencing PR group (\$554 AUD per participant; \$661 calculated in 2024 AUD when adjusting for inflation [136]) than the centre-based group (\$1298 AUD; \$1550 calculated in 2024 AUD when adjusting for inflation [136]), primarily due to a

decrease in travel-related activities. Likewise, the authors reported in a letter to the editor [210] that a reduction in participant travel was associated with a significant reduction in GHG emissions (median [IQR]; centre-based: 70 kgCO_{2e} [30 to 180]; videoconferencing PR: 30 kgCO_{2e} [10 to 60], $p < 0.001$), although this analysis accounted for staff and participant travel only and not for other potential sources of GHG emissions such as equipment and electricity use. Conversely, healthcare provider resource usage costs, as reported in the economic analysis [144], were greater for videoconferencing PR (\$1601 AUD per participant; \$1912 calculated in 2024 AUD when adjusting for inflation [136]) than centre-based PR (\$529 AUD per participant; \$632 calculated in 2024 AUD when adjusting for inflation [136]) due to higher staffing and equipment costs. The set-up and operating requirements for videoconferencing PR programs can be demanding when compared to unsupervised home-based PR programs that can be delivered with minimal resources, and centre-based PR programs that share equipment across participants and with other healthcare services.

In summary, evidence from high-quality randomised controlled trials [144, 172, 173, 208, 210] have indicated that in people with COPD, videoconferencing PR is safe and improves exercise capacity compared to standard care. Videoconferencing PR also appears to be equivalent to centre-based PR for improvements in exercise capacity, HRQoL, dyspnoea and cost-effectiveness, and possibly superior for improvements in health status and reduction in GHG emissions. Similar to centre-based PR, videoconferencing PR has little to no impact on physical activity levels. However, the generalisability of the results to people with COPD who are unwilling or unable to access centre-based PR is limited, as due to the nature of randomised controlled trials, participants were required to accept either centre-based PR or videoconferencing PR as a condition of enrolment. Additionally, 16 - 65% of eligible individuals were excluded for preferring centre-based PR [172, 173, 208] and highlights the importance of participant preference when considering reach and adoption of videoconferencing PR. Regardless, strong overall conclusions on the suitability of videoconferencing PR as an alternative to centre-based PR cannot be made as clinically significant improvements for either PR program were rare, possibly related to programs not meeting recommendations for PR exercise frequency and duration. Increasing exercise sessions to meet recommendations

would be associated with greater resource usage costs and may not be feasible for PR sites that are operating at maximal capacity. Therefore, other telerehabilitation PR models that promote unsupervised exercise sessions without increasing PR resources may be a solution to this and are examined in the subsequent sections.

Effects of Web-Based Pulmonary Rehabilitation

Web-based PR allows people with COPD to complete unsupervised, multi-component PR programs at home through a web-based platform. To date, five randomised controlled trials have evaluated the effects of web-based PR in people with COPD [193-196, 211] (summarised in Appendix 2). Studies were of moderate to high quality and were compared to either standard care [193, 211], home-based PR [194, 195] or centre-based PR [196]. Two of the randomised controlled trials [211] were multi-arm trials, comparing web-based PR and home-based PR programs to standard care [211] or an education program only [195]. The study design of the five randomised controlled trials [193-196, 211] were heterogenous, with PR program duration ranging from 11 weeks to 24 months, and web-based PR programs delivering exercise programs only or including additional interventions, such as education, goal setting and/or symptom monitoring. In one trial [211], a 24-month web-based PR program was supported by regular videoconferencing calls where healthcare professionals provided education or supervised an exercise session. Despite the differences in the randomised controlled trials [193-196, 211], the web-based PR programs included most of the essential components of PR, allowing for broad comparisons between the findings. Participants included in the randomised controlled trials represented a diverse population of people with COPD, including people with mild to very severe COPD, primary to tertiary level education, and low to high presence of comorbidities. Most participants were not working and had prior experience with the use of personal computers or the internet or had support available from carers or family members who did. Therefore, the findings presented in the following sections can be applied to people with mild to very severe COPD who have had prior experience, or can be supported with, the use of technology.

Exercise capacity

Randomised controlled trials [193, 196, 211] evaluating the effects of web-based PR on exercise capacity when compared to standard care have reported conflicting findings. Wang and colleagues [193] demonstrated that web-based PR significantly improved 6MWD (mean [SD], 297 [113] m) when compared to standard care (mean [SD], 199 [99] m, $p < 0.001$), with statistically and clinically significant within-group improvements. However, caution should be taken when interpreting these results as between-group analysis was not adjusted for the web-based PR group having a

higher, but not statistically significant, baseline 6MWD. In contrast, Zanaboni and colleagues [211] found no significant difference in the 6MWD between a 24-month web-based PR program (mean [SD], 400 [142] m) over standard care (mean [SD], 357 [102] m, between-group $p = 0.19$). Although no statistically significant difference was found, it is worth noting that the within-group difference for web-based PR exceeded the proposed MCID of 30 m, whereas standard care showed a decline in exercise capacity, similar to findings from Wang and colleagues [193]. Nguyen and colleagues [195] found no difference in 6MWD ($p = 0.21$) between web-based PR, home-based PR and standard care with education; however, statistical analyses were not performed between each group and as such, interpreting differences between web-based PR and standard care is not possible. Though the evidence is limited, the findings from these randomised controlled trials suggest that web-based PR may improve exercise capacity when compared to standard care.

An 11-week web-based PR program was found to be no different to centre-based PR for improvements in the ESWT in a randomised controlled feasibility trial [196] of moderate quality. However, between-group mean differences and results of statistical tests were not reported, significantly limiting the ability to interpret results. High-quality randomised controlled trials are needed to draw clear conclusions as to whether web-based PR is equivalent to centre-based PR for improvements in exercise capacity.

Health-related quality of life

The evidence comparing web-based PR to standard care on improvements in HRQoL are conflicting. When compared to standard care, Wang and colleagues [193] demonstrated a statistically and clinically significant between-group difference in SGRQ Total at 12 months (mean [SD], web-based PR: 31 [21] points; vs standard care: 58 [21] points; $p < .001$) favouring web-based PR, whereas the trial by Zanaboni and colleagues [211] reported no difference in EQ-VAS score (mean [SD], web-based PR: 55 [21] points; vs standard care: 50 [21] points; $p = 0.23$). Web-based PR programs in both trials [193, 211] were comprehensive and allowed participants to monitor progress and set goals; however, only the randomised controlled trial by Wang and colleagues [193] included a comprehensive education program, possibly explaining why significant improvements in HRQoL were only reported in this study.

Likewise, randomised controlled trials [194-196] of moderate to high quality demonstrated that web-based PR was equivalent to home-based PR [194, 195] and centre-based PR [196] for improvements in HRQoL. Education programs were key components of the web-based PR, home-based PR and centre-based PR programs and could explain why all groups achieved significant within-group improvements in HRQoL, measured using the CRQ questionnaire. However, there was no adjustment for baseline values and, in one trial [196], statistical analyses were not reported, significantly limiting the validity of the results.

Dyspnoea

The findings from two randomised controlled trials [193, 211] suggest that web-based PR programs may improve activity-related dyspnoea compared to standard care. Wang and colleagues [193] reported statistically significant improvements in mMRC score following web-based PR at all time points up until the end of the 12-month program (12 months: mean [SD], web-based PR: 1.1 [1.0] points; vs standard care: 2.9 [0.9] points; $p < .001$). In contrast, Zanaboni and colleagues [211] observed a statistically significant improvement in mMRC score following 6 months (mean [SD], web-based PR: 1.7 [1.2] points; vs standard care: 2.2 [0.8] points; $p = 0.037$) of web-based PR, but no difference at 12 or 24 months, suggesting a decline in benefit during the lower-intensity maintenance period. One possible explanation for the sustained improvements in Wang and colleague's trial [193] may be the more frequent and structured education program, which differed substantially from the less intensive approach used in Zanaboni and colleague's trial [211]. This variation in educational delivery and frequency of follow-up sessions may have contributed to the differences in long-term effects on dyspnoea.

Web-based PR has been shown to be comparable to both home-based PR and centre-based PR in its impact on dyspnoea, as demonstrated through three randomised controlled trials [194-196]. In two trials conducted by the same research group [194, 195], changes in CRQ dyspnoea score were the primary outcome measure and significantly improved following 6 months [194] and 12 [195] months of web-based PR and home-based PR, but did not differ between groups. The results from one trial [195] reported a trend towards improved dyspnoea over 12 months in both the web-based PR and home-based PR groups compared to a home-based education-only group, highlighting the importance of including an exercise program

to achieve improvements in dyspnoea. Similarly, in a trial that compared web-based PR and centre-based PR programs of approximately seven to eleven weeks [196], no between-group differences were found in CRQ dyspnoea score, but significant within-group differences were seen in both groups ($p < 0.001$), mirroring the significant within-group improvements seen in exercise capacity ($p < 0.001$). Given that the CRQ dyspnoea subdomain assesses activity-related dyspnoea, improvements in CRQ dyspnoea score in these trials [194-196] could be explained by the positive effect of exercise training on exercise capacity. However, interpretation of these results is limited by methodological issues, with baseline values not being adjusted for in all trials and in one trial [196], statistical analyses were not reported.

Health status

The effects of web-based PR on health status have been evaluated in only two moderate to high quality randomised controlled trials [196, 211]. In the trial by Zanaboni and colleagues [211], a small, but statistically significant, improvement in the CAT score was reported for web-based PR at six months (mean [SD], Baseline: 20 [6] points; vs 6 months: 18 [7] points) when compared to standard care (mean [SD], baseline: 20 [8] points; vs 6 months: 21 [7] points) but was not maintained at 12 months. The web-based PR program contained an eight-week intensive PR program followed by 22 months of maintenance PR, with additional sessions provided after exacerbations of COPD. Whether participants had greater improvements in the CAT score after the eight-week PR program is unknown, but the findings suggest that improvements in clinical outcomes immediately after web-based PR intervention are lost over the maintenance period. When compared to centre-based PR, another randomised controlled trial [196] reported that web-based PR was no different; however, no data was provided to confirm these findings. High-quality evidence investigating the effects of web-based PR on health status is scarce, underscoring the need for further rigorous research to draw definitive conclusions.

Physical activity

The effects of web-based PR on physical activity levels have not been evaluated in any randomised controlled trial. Further research is needed to determine whether this model of PR can successfully improve physical activity levels when compared to centre-based PR.

Self-efficacy

Of the five randomised controlled trials evaluating web-based PR, only three [194, 195, 211] evaluated changes in self-efficacy. Zanaboni and colleagues [211] demonstrated that neither web-based PR nor home-based PR improved GSES scores compared to standard care over 24 months (mean [SD], web-based PR: 30 [6] points; home-based PR: 31 [5] points; vs standard care: 33 [6] points). This lack of effect occurred despite the inclusion of ad hoc, individualised education and self-management interventions through a website, suggesting that the frequency or structure of education may have been insufficient, or that the GSES may lack sensitivity to detect change following PR [114]. In contrast, a 2008 trial conducted by Nguyen and colleagues [194] evaluated a web-based PR and home-based PR program which incorporated regular individualised and structured education and self-management interventions and found that both PR programs improved dyspnoea related self-efficacy and knowledge over 6 months, with no significant difference between the two groups for either outcome [194]. A subsequent trial by the same authors [195] compared similar web-based PR and home-based PR programs to a home-based education-only intervention and observed a trend toward greater improvements in self-efficacy in the PR groups (mean [95% CI], web-based PR: 7 [6 to 8] points; home-based PR: 6 [5 to 7]; vs. education only: 6 [5 to 7] points; $p = 0.06$) [195]. However, these findings should be interpreted with caution, as both trials used custom-designed questionnaires to assess self-efficacy and knowledge and consequently, lack established validity and reliability and limit confidence in the results. Further research is required to determine whether integrating structured education and self-management interventions into a web-based PR program can meaningfully enhance self-efficacy, and to identify the optimal frequency and format required to achieve sustained improvements.

Adverse events

Adverse events were infrequently reported in the randomised controlled trials, with two trials [196, 211] including it as an outcome measure, and just one [211] presenting the findings. Zanaboni and colleagues [211] reported that only minor adverse events occurred and were related to medical problems and issues with treadmill function. Another trial [194] reported 26% of participants experienced an exacerbation of COPD, but other adverse events were not monitored. Due to the

limited evidence, the safety of web-based PR cannot be determined. Future studies investigating web-based PR should monitor and report any adverse events so that conclusions regarding safety can be made.

Technological issues

Randomised controlled trials that reported on technological issues associated with web-based PR were scarce. A single trial [194] reported technological issues and usability challenges which were so significant that it was necessary to stop the trial early. The majority of the technological issues were associated with accessing the web-based PR platform as participants needed to install proprietary security software, disable pop-up blocker software programs and could only access the web-based PR platform on a certain web-browser. The authors noted that these issues could only be resolved with a complete redesign of the web-based PR platform. The authors have since published a larger web-based PR randomised controlled trial [195], although were similarly unable to reach adequate statistical power and made no comments as to why this was the case or if any further technological issues occurred. The findings highlight the potential risk to PR program if web-based platforms encounter significant technological issues, and the need for reliable and robust technological infrastructure when considering the remote delivery of PR.

Engagement

Engagement with web-based PR programs were described in two randomised controlled trials [194, 195] and were measured through automated system-recorded data recorded by the web-based PR platform. In the 2008 trial by Nguyen and colleagues [194], overall engagement with the web-based platform was low, marked by participants accessing the platform a mean 59 times within a 6-month period. Engagement was highest with recording exercises (mean [SD], 156 [80] entries) and symptoms (mean [SD], 136 [48] entries), and lowest with the exercise goal-setting tool (mean [SD], 4 [6] entries). Participants reported that slow loading of the web-based platform and security concerns discouraged them from accessing the program more regularly. The same authors published a larger randomised controlled trial [195] five years later and engagement improved significantly, with 75% of participants accessing the web-based platform at least once over the 12 months and, on average, once every second day (mean [SD], 178 [133] times). The findings

emphasise the value of web-based platforms in tracking engagement trends to multiple program components.

Adherence

Only a single randomised controlled trial [195] presented findings on exercise adherence. Results showed that web-based PR resulted in a significant improvement in endurance duration and resistance session frequency per week at 12 months; however, this was not statistically different when compared to home-based PR or education alone. Another trial [194] reported that more participants were adherent to at least six education sessions in the web-based PR group (96%) than in the home-based PR group (80%). Lower adherence rates in the home-based PR group may have been a consequence of participants needing to travel to face-to-face group sessions, whereas the web-based PR participants completed education sessions from home through the web-based PR platform. Further research evaluating adherence to web-based PR programs is vital to determine whether this model is a viable option for people with COPD.

Economic and environmental impact

To date, there have been no economic or environmental analyses on the delivery of web-based PR programs to people with COPD. Future economic and environmental evaluations are needed to help guide policymakers to determine whether web-based PR should be implemented into clinical practice.

Overall, the evidence for the effects of web-based PR in people with COPD when compared to standard care or centre-based PR remains unclear. Moderate to high quality evidence suggests that web-based PR is possibly superior to standard care, and equivalent to centre-based PR for improvements in exercise capacity in people with COPD. However, the effects of web-based PR on other clinical outcomes are less convincing. Findings have highlighted the fragility of web-based PR when significant technological issues occur, and the need for robust technological infrastructure when delivering web-based PR and other telerehabilitation PR programs. Substantial research is still needed to determine whether web-based PR is a viable alternative to centre-based PR. However, web-based PR remains a promising alternative PR model that warrants further investigation as two trials [194, 196] found that more participants preferred web-based PR (36 to 38%) to centre-

based PR (31%). Although only a small percentage of participants were excluded due to a lack of internet (17%) [196] or computer access (7%) [195], the widespread availability of mobile devices and offline capabilities of mHealth apps give mHealth PR clear advantages over videoconferencing PR and web-based PR. These advantages warrant further attention in future research.

Effects of mHealth Pulmonary Rehabilitation

Increasing global interest in mHealth has resulted in numerous studies that have examined the acceptability, feasibility and effectiveness of mHealth PR in people with COPD. To date, 18 studies [16, 17, 212-227] have examined the effects of 14 mHealth PR apps on clinical outcomes. The studies have been heterogenous in design and have included nine randomised controlled trials [16, 17, 212-218] (reported in Table 1.1), three feasibility single-arm studies [222, 225, 226], two observational studies [221, 224], three controlled clinical trials [219, 220, 223] and one cohort study [227] (all studies except randomised controlled trials are summarised in Appendix 3). mHealth PR app features (Table 1.2) and the presence of PR essential components (Table 1.3) have varied greatly between mHealth PR studies, such that some of the studies could be considered not to be offering a PR program. Studies that have solely detailed mHealth PR platform development or have used mHealth to support centre-based PR, maintenance or physical activity programs are beyond the scope of this thesis.

Table 1.1. Clinical trials investigating the effects of mHealth PR in people with COPD (randomised controlled trials only)

Author (Year), App Name, Country, FEV ₁ % pred, N (IG/CG)	Essential PR, PEDro	Intervention Program	Comparison Program	Between-Group Results
Benzo [212] (2021) 'Mindful Breathing Lab' USA FEV ₁ %pred: IG = 43% (19) CG = 42% (15) N: 72 / 74	PR: 3 PEDro: 4	IG: mHealth PR. 6 x 12 min unsupervised sessions.week ⁻¹ . 8 weeks. <u>Education:</u> Nil. <u>Self-management:</u> Symptom, exercise and physical activity monitoring through app. <u>Follow-up:</u> Supported by weekly telephone calls. <u>Equipment:</u> Tablet, pulse oximeter and activity monitor provided.	CG: standard care	MD (SD) Ex capacity: n.m Health status n.m HRQoL: CRQ-Physical: IG: 0.2 points (1.0) vs CG: 0.0 points (0.7) Dyspnoea: CRQ-Dyspnoea: IG: 0.4 points (1.1) vs CG: 0.0 points (1.1) PA: Daily steps: IG: -344 steps (1658) vs CG: -976 steps (2596) Self-efficacy: SMAS-30: IG: 3.2 points (7.4)* vs CG: -0.9 points (5.9) AE: No AE Technology: n.m Adherence: Exercise: IG: 86% Engagement: Videos watched >6000 time Economic: n.m Environment: n.m
Crooks [213] (2020) 'myCOPD' UK FEV ₁ %pred: nil N: 29 / 31	PR: 2 PEDro: 7	IG: mHealth app with optional PR. 12 weeks. Participants were given no instructions on how to use the app. Multiple modules within app with one module 'pulmonary rehabilitation'. <u>Education:</u> Education and inhaler videos on app. <u>Self-management:</u> Medication diary and action plan on app. <u>Follow-up:</u> Nil. <u>Equipment:</u> Activity monitor provided for sub-study.	CG: standard care	MD (95% CI) Ex capacity: n.m Health status CAT: 1.3 points (-4.5 to 1.9) HRQoL: EQ-5D VAS: 0.9 points (-9.5 to 11.2) Dyspnoea: n.m PA: Daily steps (n = 14): -2253 steps (-10,434 to 5928) Self-efficacy: n.m AE: IG = 5 vs CG = 7 (details not specified) Technology: n.m Adherence: App: Decline over time. -0.2 pts (0.7 to 0.3) increase in CAT with every 7 days increase app usage. ≥ 60 days use: 13% Engagement: Accessed app once: 33% Economic: n.m Environment: n.m

Table 1.1 continued.

<p>Kwon [216] (2018) 'efil breath' Republic of Korea <u>FEV₁ %pred:</u> IG 1 = 59% (16) IG 2: 57% (17) CG = 56% (15) <u>N:</u> 27 / 30 / 28</p>	<p><u>PR:</u> 10 <u>PEDro:</u> 3</p>	<p>IG 1: mHealth PR (fixed regime). 7 unsupervised sessions.week⁻¹. 12 weeks. IG 2: mHealth PR (interactive regime). First 6 weeks fixed regime + 6 weeks progress by Borg 3. IG 1 and 2: <u>Education:</u> Nil <u>Self-management:</u> Exercise diary <u>Follow-up:</u> Nil. <u>Equipment:</u> Pulse oximeter provided.</p>	<p>CG: standard care</p>	<p>No data, graph only. No between-group comparison. Ex capacity: 6MWD: no significant within-group differences IG 1, IG 2 and CG Health status CAT: significant within-group difference IG 1, not for IG 2 or CG HRQoL: n.m Dyspnoea: mMRC: no significant within-group differences IG 1, IG 2 and CG PA: n.m Self-efficacy: n.m AE: n.m Technology: n.m Adherence: n.m Engagement: n.m Economic: n.m Environment: n.m</p>
<p>North [218] (2020) 'myCOPD' UK <u>FEV₁ %pred:</u> IG = 47% (18) CG = 42% (18) <u>N:</u> 21 / 20</p>	<p><u>PR:</u> 5 <u>PEDro:</u> 7</p>	<p>IG: mHealth app with optional PR. 90 days. Instructed to use at least weekly, encouragement focused on self-monitoring and education modules. Multiple modules within app with one module 'pulmonary rehabilitation'. <u>Education:</u> Education and inhaler videos on app. <u>Self-management:</u> Medication diary and action plan. <u>Follow-up:</u> Nil. <u>Equipment:</u> Nil.</p>	<p>CG: standard care <u>Education:</u> Paper-based education booklet. <u>Self-management:</u> Paper-based symptom and medication action plan.</p>	<p>MD (95% CI) Ex capacity: n.m Health status CAT: -2.9 points (-6.9 to 1.0) HRQoL: SGRQ Total: -1.5 points (-7.8 to 4.8) Dyspnoea: mMRC: 0.02 points (-0.8 to 0.8) PA: n.m Self-efficacy: n.m AE: Mild: IG: 1 vs CG: 0; Severe: IG: 2 vs CG: 1 (unrelated to study) n.m Technology: n = 40% used app more than once.week-1 Adherence: n = 85% activated the app. Decline in app users over time. Mean Engagement: (SD) days app used 4.8 (0.6) Economic: n.m Environment: n.m</p>

Table 1.1 continued.

<p>Gloeckl [214] (2024) 'Kaia COPD' <u>Germany</u> <u>Switzerland</u> <u>FEV₁ %pred</u> median (IQR): IG = 48% (36 to 57) CG = 48% (40 to 61) <u>N</u>: 136 / 142</p>	<p><u>PR</u>: 8 <u>PEDro</u>: 7[‡]</p>	<p>IG: mHealth PR. 7 x 15-20 min unsupervised sessions.week⁻¹. 12 weeks. <u>Education</u>: Inhaler videos and education through app. <u>Self-management</u>: Self-management program described as exercise training, education and breathing exercises. <u>Follow up</u>: Telephone calls fortnightly to collect AE data. Motivational telephone calls if app usage < 3 days. <u>Equipment</u>: smartphone.</p>	<p>CG: home-based PR. 7 x 15-20 min unsupervised sessions.week⁻¹. 12 weeks. <u>Education</u>: Paper-based education booklet. <u>Self-management</u>: Paper-based exercise diary. <u>Follow up</u>: Telephone calls fortnightly for motivation.</p>	<p>Median (IQR) Ex capacity: 1minSTS: 1 repetition (0 to 2) Health status CAT: 0 points (-1 to 2) HRQoL: VR-12: -2 points (-5 to 1) Dyspnoea: n.m PA: n.m Self-efficacy: n.m AE: IG: 41% vs CG: 41% (unrelated to study) Technology: 2 dropouts due to technological problems Adherence: Exercise: IG: 41% vs CG: 72%. Weekly trend: Exercise stable over 12 weeks, education and self-management declined after 20 days. Engagement: 23 (11 to 46) exercise entries in total. Higher engagement with exercise than education or self-management Economic: n.m Environment: n.m</p>
<p>Liu [217] (2008) No Name <u>Taiwan</u> <u>FEV₁ %pred</u> IG = 45% (3) CG = 46% (3) <u>N</u>: 24 / 24</p>	<p><u>PR</u>: 8 <u>PEDro</u>: 4</p>	<p>IG: mHealth PR. 7 unsupervised sessions.week⁻¹. 3 months PR + 9 months maintenance. <u>Education</u>: Nil. <u>Self-management</u>: Nil. <u>Follow up</u>: Telephone calls if 1 day of exercise missed. Clinic visit every 4 weeks. <u>Equipment</u>: smartphone.</p>	<p>CG: Telephone home-based PR. 7 unsupervised sessions.week⁻¹. 3 months PR + 9 months maintenance. <u>Education</u>: Nil. <u>Self-management</u>: Nil. <u>Follow up</u>: Fortnightly telephone calls for motivation. Clinic visit every 4 weeks.</p>	<p>Mean (SD) Ex capacity: ISWT: 12 weeks IG: 324 m (23)* vs Baseline CG: 256 m (21) Health status n.m HRQoL: SF-12 PCS: IG: 45 points (1)* vs CG: 34 points (2) Dyspnoea: Borg (after ISWT): IG: 3 points (0.1)* vs CG: 4.3 points (0.1) PA: n.m Self-efficacy: n.m AE: No AE related to study. Hospitalisations: IG: 8% vs CG: 33% Technology: 4 dropouts due to difficulty using smartphone Adherence: Exercise: 12 weeks: IG: 92%* vs CG: 38% Engagement: n.m Economic: n.m Environment: n.m</p>

Table 1.1 continued.

<p>Bourne [16] (2017) UK <u>FEV₁ %pred:</u> IG = 61% (20) CG = 58% (24) <u>N:</u> 64 / 26</p>	<p><u>PR:</u> 7 <u>PEDro:</u> 8</p>	<p>IG: mHealth PR. 2-5 x 10-35 min unsupervised sessions.week⁻¹. 6 weeks. <u>Education:</u> Education videos (3 videos.week⁻¹) on app. <u>Self-management:</u> Nil. <u>Follow up:</u> Weekly telephone calls to collect AE data. <u>Equipment:</u> nil</p>	<p>CG: centre-based PR. 2 x 10-35 min supervised sessions.week⁻¹. 6 weeks. <u>Education:</u> Same content as IG, presented orally. <u>Self-management:</u> Nil.</p>	<p>MD (95% CI) Ex capacity: 6MWD: 24 m (-5 to 52)[‡] Health status CAT: -1.0 points (-2.9 to 0.9)[‡] HRQoL: SGRQ Total: -3.7 points (-10.7 to 3.3)[‡] Dyspnoea: mMRC: 0.03 points (-0.6 to 0.6) PA: n.m Self-efficacy: n.m AE: Minor: IG: 2 vs CG: 2. No serious. (unrelated to study) Technology: 'very little additional support...most issues resolved remotely' Adherence: Exercise: IG: 62% vs CG: 72%. Engagement: Decline in participation with exercise sessions over time in IG Economic: n.m Environment: n.m</p>
<p>Cerdan-de-las-Heras [17] (2021) Denmark <u>FEV₁ %pred:</u> IG = 36% (14) CG = 33% (9) <u>N:</u> 27 / 27</p>	<p><u>PR:</u> 11 <u>PEDro:</u> 4</p>	<p>IG: mHealth PR. 3-5 x 10-20 min unsupervised sessions.week⁻¹. 8 weeks <u>Education:</u> 'E-learning packages' on app. <u>Self-management:</u> Nil. <u>Follow up:</u> Videoconferencing calls (unspecified frequency) <u>Equipment:</u> nil</p>	<p>CG: centre-based PR. 2 x 60 min supervised sessions.week⁻¹. 8 weeks. <u>Education:</u> 6 hours of education in total. <u>Self-management:</u> Nil.</p>	<p>MD (95% CI) at 8-week timepoint, not adjusted for baseline Ex capacity: 6MWD: 47 m (-16 to 111)[‡] Health status: n.m HRQoL: SGRQ Total: -2.1 pts (-11.9 to 7.6)[‡] Dyspnoea: n.m PA: Daily steps: -3609 steps (-9652 to 2433) Self-efficacy: n.m AE: no AE Technology: 1 drop out due to 'sensor problems' Adherence: Exercise: 82% - uncertain whether IG, CG or combined Engagement: n.m Economic: n.m Environment: n.m</p>

Table 1.1 continued.

				mean (SD)
Jiang [215] 2020	PR: 9	IG: mHealth PR. ≥ 3 x	CG: centre-based PR.	
'WeChat'	PEDro: 6	20-30 min	≥ 3 20-30 min	Ex capacity: n.m
China		unsupervised	supervised	Health status: CAT: No significant difference between groups ($p = 0.98$)
FEV ₁ %pred: nil		sessions.week ⁻¹ . 3	sessions.week ⁻¹ . 3	HRQoL: SGRQ Total: No significant difference between groups (did not adjust for baseline)
GOLD II-III: 84%		months	months	Dyspnoea: mMRC: No significant difference between groups ($p = 0.43$)
N: 53 / 53		Education: Audio and graphic education on app.	Education: Not clear	PA: n.m
		Self-management: Medication and diet guidance, share progress with peers.	Self-management: Not clear.	Self-efficacy: Ex-SRES: No significant difference between groups ($p = 0.14$)
		Follow up: Nil, participant can contact through app if unwell		AE: n.m
		Equipment: resistance bands		Technology: n.m
				Adherence: n.m
				Engagement: n.m
				Economic: n.m
				Environment: n.m

PR score is the total number of PR essential components [6] that were included in the intervention group out of a possible 13 essential components. PEDro scale [228] is a measure of the methodological quality of clinical trials and is a score out of 10.

*statistically significant between-group difference. †results indicate non-inferiority of mHealth PR. ‡PEDro score not previously completed and was calculated for this table with the following results: Eligibility criteria: Yes; Random allocation: Yes; Concealed allocation: No; Baseline comparability: Yes; Blind subjects: No; Blind therapists: No; Blind assessors: No; Adequate follow-up: Yes; Intention-to-treat analysis: No; Between-group comparisons: Yes; Point estimates and variability: Yes. Note: Eligibility criteria item does not contribute to total score.

1minSTS: one-minute sit-to-stand test; 6MWD: six-minute walk distance; AE: adverse event; CAT: COPD Assessment Test; CG: comparison group; COPD: chronic obstructive pulmonary disease; CRQ: Chronic Respiratory Disease Questionnaire; education: education component of program; EQ-5D VAS: European Quality of Life five-dimension visual analogue scale; equipment: any equipment provided to the participants; Ex-SRES: Exercise Self-Regulatory Efficacy Scale; FEV₁%pred: percent predicted forced expiratory volume in one second; follow up: follow up contact with a healthcare professional; GOLD: The Global Initiative for Chronic Obstructive Lung Disease spirometry criteria for airflow limitation severity; IG: intervention group; ISWT: incremental shuttle walking test; MD: mean difference; mHealth: mobile health; mins: minutes; mMRC: modified Medication Research Council dyspnoea scale; N: number of participants recruited; n.m: not measured; PEDro: Physiotherapy Evidence Database; PR: pulmonary rehabilitation; RCT: randomised controlled trial; SD: standard deviation; self-management: self-management intervention provided to participants; SF-12 PCS: 12-item Short Form survey physical components section; SGRQ: St George's Respiratory Questionnaire; SMAS-30: Self-Management Ability Scale – 30 items; UK: the United Kingdom; USA: the United States of America; VR-12: Veterans RAND 12-item health survey.

Table 1.2. mHealth PR app features used in mHealth PR studies

Author (Year) 'App Name'	Exercise	Education	Symptom	Observation	Medication	Action plan	Motivation	Physical activity	Contact with HCP	Contact with peers	Customised	Web-based platform
Randomised controlled trials												
Benzo [212] (2021) 'Mindful Breathing Lab'	✓		✓	✓			✓	✓				✓
Bourne [16] (2017) 'myCOPD'	✓	✓										
Cerdan-de-las-Heras [17] (2021) 'Optimov'	✓	✓	✓	✓					✓		✓	✓
Crooks [213] (2020) 'myCOPD'	✓	✓	✓		✓	✓		✓				
Gloeckl [214] (2024) 'Kaia COPD'	✓	✓				✓	✓		✓		✓	✓
Jiang [215] (2020) 'WeChat'	✓	✓			✓	✓	✓		✓	✓	✓	✓
Kwon [216] (2018) 'efil breath'	✓			✓							✓	✓
Liu [217] (2008) 'No name'	✓		✓								✓	✓
North [218] (2022) 'myCOPD'	✓	✓	✓		✓	✓						
Non-randomised controlled trials												
Barata [219] (2022) 'Pneumocontrol'	✓	✓	✓								✓	
Candy [220] (2023) 'mPR'	✓	✓	✓					✓	✓		✓	✓
Cooper [221] (2022) 'myCOPD'	✓	✓	✓		✓	✓						
Deng [222] (2021) 'WeChat'	✓		✓						✓		✓	✓
Flynn [223] (2025) 'Health in motion'	✓	✓	✓	✓		✓					✓	✓
Rassouli [224] (2018) 'Kaia COPD'	✓	✓	✓					✓	✓		✓	
Whittaker [225] (2021) 'mPR'	✓	✓	✓			✓					✓	✓
Yonchuk [226] (2022) 'Respercise'	✓	✓						✓				
Zhang [227] (2022) 'Xeek'	✓	✓	✓	✓							✓	✓

mHealth PR apps and reported features. Versions of the apps with the same name may have been investigated in more than one study.
 Exercise: exercises can be viewed or recorded on app; Education: written, visual or audio education content available on app; Symptom: recording of symptoms within app often in form of questionnaire;
 Observation: medical observations (e.g. oxygen saturation, heart rate, blood pressure) are manually or automatically recorded on to app; Medication: view or record usual medications; Action plan: medication action plan can be viewed or recorded on app; Motivation: motivational feature integrated into app (e.g. rewards, review graph of progress); Physical activity: physical activity feature (e.g. daily step count);
 Contact with HCP: communication with a healthcare professional through the app; Contact with peers: communication or interactions with peers through the app; Customisable: app is customisable to the individual (may be manually customised by a healthcare professional or automatically done through app algorithms); Web-based platform: web-based platform that can be used by healthcare professionals to view app data (e.g. adherence, medical alerts).
 ✓: app feature was reported in paper.

Table 1.3. The essential components of PR included in mHealth PR studies

Author (Year) 'App Name'	Centre-based assessment	Exercise test	Field exercise test	HRQoL	Dyspnoea	Nutritional status	Occupational status	Endurance	Resistance	Individually prescribed	Individually progressed	HCP experience	HCP trained
Randomised controlled trials													
Benzo [212] (2021) 'Mindful Breathing Lab'				✓	✓								✓
Bourne [16] (2017) 'myCOPD'	✓	✓	✓	✓	✓				✓				✓
Cerdan-de-las-Heras [17] (2021) 'Optimov'	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓
Crooks [213] (2020) 'myCOPD'				✓					✓				
Gloeckl [214] (2024) 'Kaia COPD'		✓	✓	✓		✓			✓	✓	✓		✓
Jiang [215] (2020) 'WeChat'	✓			✓	✓	✓			✓	✓	✓	✓	✓
Kwon [216] (2018) 'efil breath'	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓		
Liu [217] (2008) 'No name'	✓	✓	✓	✓	✓	✓		✓		✓			
North [218] (2022) 'myCOPD'	✓			✓	✓				✓				✓
Non-randomised controlled trials													
Barata [219] (2022) 'Pneumocontrol'	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓
Candy [220] (2023) 'mPR'	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Cooper [221] (2022) 'myCOPD'									✓				
Deng [222] (2021) 'WeChat'	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓
Flynn [223] (2025) 'Health in motion'	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓
Rassouli [224] (2018) 'Kaia COPD'				✓	✓	✓		✓	✓	✓	✓		
Whittaker [225] (2021) 'mPR'	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓
Yonchuk [226] (2022) 'Respercise'	✓	✓	✓			✓			✓	✓	✓	✓	✓
Zhang [227] (2022) 'Xeek'	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
<p>mHealth PR programs and essential components of PR that are reported in the clinical trials. Versions of the apps with the same name may have been investigated in more than one study. The 13 essential components of PR have been published previously [6] and include: 1) Centre-based assessment: an initial centre-based assessment by a healthcare professional; Exercise test: an exercise test at the time of assessment; Field exercise test: A field exercise test performed; HRQoL: health-related quality of life measure taken; Dyspnoea: Dyspnoea assessment; Nutritional status: nutritional status evaluation; Occupational status: occupational status evaluation; Endurance: endurance training; Resistance: resistance training; Individually prescribed: an exercise program that is individually prescribed; Individually progressed: an exercise program that is individually progressed; HCP experience: team includes a healthcare professional with experience in exercise prescription and progression; HCP trained: healthcare professionals are trained to deliver the components of the model that is deployed.</p> <p>✓: PR program component was reported in paper.</p>													

Given the extensive number of mHealth PR studies available, only the nine randomised controlled trials [16, 17, 212-218] will be included in the subsequent sections discussing the effectiveness of mHealth PR. The randomised controlled trials ranged from low to high quality [228] and compared mHealth PR to either standard care [212, 213, 216, 218], home-based PR [214, 217] or centre-based PR [16, 17, 215]. The majority of the mHealth PR programs were delivered over eight to 12 weeks [16, 17, 212, 213, 216], with one as short as six weeks [16] and others greater than three months [214, 215, 217, 218]. Although no mHealth PR program contained all essential components of PR, six trials [16, 17, 214-217] included at least seven essential components and two trials [17, 216] included at least 10. Collectively, the randomised controlled trials evaluated the effects of mHealth PR in people with mild to very severe COPD who may or may not have had prior experience with technology use.

Exercise capacity

Based on evidence from five randomised controlled trials [16, 17, 214, 216, 217] of varying quality, the effects of mHealth PR on exercise capacity in people with COPD remains unclear. Only one low-quality trial [216] has compared mHealth PR to standard care and reported no improvement in the 6MWD in either group, but interpretation of these findings is significantly limited due to the absence of between-group comparisons and the lack of data on within-group differences. When mHealth PR was compared to home-based PR, two moderate to high quality randomised controlled trials [214, 217] reported conflicting results for improvements in exercise capacity, with Gloeckl and colleagues [214] finding no difference (one-minute sit-to-stand [1minSTS] median 1 repetition, IQR 0 to 2) and Liu and colleagues [217] superiority (ISWT mean [SD], mHealth PR at 12 weeks: 324 [23] m; vs home-based PR at baseline: 256 [21] m; $p < 0.001$) of mHealth PR. While the mHealth PR and home-based PR groups in the trial by Gloeckl and colleagues [214] showed statistically significant improvements in 1minSTS, neither reached the MCID of 3 repetitions [229]. This could be explained by the absence of endurance training in both programs, which has been shown to yield greater improvements in exercise capacity than resistance training alone [186]. In contrast, the inclusion of moderate-intensity endurance training in the trial by Liu and colleagues [217] resulted in the mHealth PR group achieving statistically and clinically significant improvements in

the ISWT (MD [SD], 68 [47] m). Both trials were significantly limited by adherence bias that affected either the mHealth PR group [214], or the home-based PR group [217], and consequently limits the validity of the findings.

Evidence from two moderate to high quality randomised controlled trials [16, 17] suggest that mHealth PR is non-inferior to centre-based PR for improvements in the 6MWD. However, Bourne and colleagues [16] found that among adherent participants there was a non-significant trend towards greater improvement in 6MWD following a six-week mHealth PR program (MD 26 m, 95% CI -1 to 53, $p = 0.06$), while Cerdan-de-las-Heras and colleagues [17] reported a similar trend favouring an eight-week mHealth PR program at six months follow up (MD 95 m, 95% CI -3 to 193, $p = 0.06$). These findings may have been a consequence of the centre-based PR groups being underpowered to detect change and, in one trial [17], the centre-based PR group was significantly older, with more severe COPD compared to the mHealth PR group. Furthermore, the mHealth PR program examined by Bourne and colleagues [16] did not incorporate an exercise program featuring endurance training, nor was it individually prescribed or progressed, possibly underestimating the true effects of both mHealth and centre-based PR. Cerdan-de-las-Heras and colleagues [17] delivered PR programs with most essential components of PR; however, the wide confidence intervals around the mean estimates lowers the certainty of the results.

Overall, there is insufficient evidence to determine whether mHealth PR improves exercise capacity in people with COPD when compared to standard care. Although there is some evidence that mHealth PR may be no different to home-based PR and centre-based PR for improvements in exercise capacity, there are significant limitations with methodological quality and the validity of results that prevent firm conclusions from being drawn. Further high-quality trials are required to determine whether mHealth PR can achieve similar improvements in exercise capacity to centre-based PR in people with COPD and should include programs that meet the essential components of PR. This has been addressed through the randomised controlled equivalence trial presented in Chapter 2 that has evaluated the effects of an mHealth PR program with all essential and desirable components of PR when compared to centre-based PR.

Health-related quality of life

The effects of mHealth PR on HRQoL in people with COPD have been examined in seven randomised controlled trials [16, 17, 212, 213, 215, 217, 218] of moderate to high quality. Findings from three trials [212, 213, 218] found no significant difference between mHealth PR and standard care for improvements in HRQoL when measured using the CRQ (Physical domain MD [SD]: mHealth PR 0.2 [1.0] points; vs standard care 0.0 [0.7] points, $p = 0.11$), EQ-5D Visual Analogue Scale (EQ-5D VAS) (MD 0.9 points, 95% CI -9.5 to 11.2) and SGRQ Total (MD -1.5 points, 95% CI -7.8 to 4.8). However, these findings were likely attributed to the mHealth PR programs delivering fewer than five essential components of PR, suggesting that they may not have had enough of the necessary components to improve HRQoL. In contrast, when an mHealth PR program delivered most of the essential components of PR [217], improvements in HRQoL were significantly greater (Short Form-12 MD [SD], mHealth PR: 45 [1] points; vs home-based PR: 34 [1.5] points, $p < .001$) when compared to home-based PR, underscoring the importance that mHealth PR programs should include the essential components of PR. Likewise, randomised controlled trials with at least seven essential components of PR were found to be non-inferior or no different to centre-based PR for improvements in the SGRQ. However, only the trial by Jiang and colleagues [215] showed statistically and clinically significant improvements in SGRQ (mean [SD], baseline: 46 [21] points; vs 6 months: 40 [21] points; $p < 0.001$) in the mHealth PR group. While all three mHealth PR apps included features other than an exercise program (Table 1.2), the mHealth PR app examined by Jiang and colleagues [215] uniquely included motivational features, using loyalty rewards, and the ability to connect with other participants online. It remains unclear whether these had a positive effect on HRQoL as engagement with the different mHealth PR app tasks was not measured. Overall, these findings suggest that further high-quality research is needed to determine whether an mHealth PR program, which includes all essential components of PR, is equivalent to centre-based PR for improvements in HRQoL. Consideration should also be given to determine which mHealth PR features people with COPD engage with to help interpret clinical findings.

Dyspnoea

Across six moderate to high quality randomised controlled trials [16, 212, 215-218], findings suggest that mHealth PR has little to no impact on dyspnoea levels when compared to standard care [212, 216, 218], home-based PR [217] or centre-based PR [16, 215]. In the one trial [212] which evaluated dyspnoea as the primary outcome, results showed no significant differences in dyspnoea between mHealth PR and standard care (within-group MD [SD], mHealth PR: 0.4 [1.1]; vs standard care: 0.0 [1.1]) Likewise, another trial [218] found no significant changes in mMRC score (MD: 0.02 points, 95% CI -0.8 to 0.9) when mHealth PR was compared to standard care. The lack of effectiveness may be attributed to the limited inclusion of essential PR components in these mHealth PR programs. In contrast, a randomised controlled trial that incorporated eight essential components of PR trial found a statistically significant reduction in dyspnoea with mHealth PR, as measured by the Borg scale on exertion (mean [SD], mHealth PR: 3 [0.1] points; vs home-based PR: 4.3 [0.1] points; $p < 0.01$) compared to home-based PR. However, the within-group differences did not reach clinical significance, considering an MCID of 2 points [230]. Similarly, improvements in mMRC score observed in two mHealth PR programs with seven [16] and nine [215] essential components were comparable to those seen following centre-based PR programs (Bourne: MD 0.03 points, 95% CI -0.6 to 0.6; Jiang, mean [SD]: mHealth PR: 2.5 [0.7]; vs centre-based PR: 2.6 [0.7], $p = 0.43$). The clinical relevance of these results is questionable due to the small changes in mMRC score, potentially reflecting the lack of responsiveness of the mMRC scale to changes in dyspnoea following PR [95]. Overall, it appears that the success of mHealth PR in improving dyspnoea may depend on the quality of the PR programs delivered. However, this remains to be tested with an mHealth PR program that includes all essential components of PR.

Health status

Randomised controlled trials [213, 216, 218] of low to moderate quality have provided little clarity on the effects of mHealth PR on health status in people with COPD when compared to standard care. Only one trial [216] included sufficient PR components to be reliably considered a PR program and found a significant within-group improvement in the CAT score following mHealth PR; however, failed to analyse between-group differences relative to standard care. No statistically

significant between-group differences for improvement in health status were found in two moderate quality randomised controlled trials [213, 218] evaluating the same multi-component mHealth PR app against standard care. Whether these findings can be attributed to PR is uncertain, as participants were either given no instructions on which intervention to use [213] or were only encouraged to complete the education and self-management tasks [218]. Overall, these findings highlight the lack of available evidence to determine the effectiveness of mHealth PR on improvements in health status in people with COPD when compared to standard care.

One high-quality randomised controlled trial [214], mHealth PR was found to be comparable to home-based PR for improvements in health status (median difference, 0 points, IQR -1 to 2, $p = 0.697$), with both groups achieving statistically and clinically significant improvements in the CAT score. Although these results were in the presence of significant improvements in exercise capacity, the authors observed that, after adjusting for exercise adherence, CAT scores did not change, while a statistically significant improvement was found in 1minSTS repetitions. These findings suggest that improvements in health status may not be solely attributed to changes in exercise capacity and a closer examination of how people with COPD engage with other mHealth PR app features may help determine the mechanisms that optimise health status.

Two high quality randomised controlled trials [16, 215] have found that mHealth PR was no different ($p = 0.98$) [215] or non-inferior (MD -1 point, 95% CI -3 to 1) [16] to centre-based PR for improvements in CAT score. However, within-group changes were small, with neither centre-based PR group achieving clinical significance. Exercise programs in both trials either did not deliver endurance training [16] or did not reach guideline recommendations [215] for exercise intensity [231]. Moderate or high intensity endurance training is considered essential for PR to be clinically effective [1], and, as such, the findings from these trials may underrepresent the true effects of mHealth PR on health status when PR standards are met. Further research is needed to determine whether an mHealth PR program with all components of PR has differing effects on health status and is addressed by the randomised controlled trial in Chapter 2.

Physical activity

The effects of mHealth PR on physical activity levels have been evaluated in three moderate to high quality randomised controlled trials [17, 212, 213]. In these trials, daily step count did not improve when mHealth PR was compared with either standard care or centre-based PR. In fact, two trials [17, 212] reported a decline in daily step count, while another observed a small improvement which was lower than that seen in the standard care group (MD -2252 daily steps, 95% CI -10,434 to 5928). However, the mHealth PR group in the latter study had significantly lower baseline physical activity levels than those in the standard care group, and when accounting for this, within-group improvements in daily step count were approximately a 10% increase for both groups. Physical activity interventions, beyond exercise training, were included in only one study [212] by providing participants with a wrist-worn activity monitor and the ability to monitor daily step count on the mHealth PR app. Despite these additional interventions, both groups saw a decline in daily step count (MD [SD], mHealth PR: -345 [1658] steps; vs standard care: -976 [2596] steps; $p = 0.13$). Due to the limited evidence available, further research is needed to determine whether mHealth PR, with the addition of targeted physical activity interventions, is a viable PR model that can improve physical activity levels.

Self-efficacy

To date, only two randomised controlled trials [212, 215] have explored the effects of mHealth PR on self-efficacy. In one trial, Benzo and colleagues [212] evaluated an eight-week mHealth PR program and reported a significant improvement in general self-efficacy, as measured by the 30-item Self-Management Ability Scale (SMAS-30), compared with standard care (MD [SD], mHealth PR: 3.2 [7.4] points; vs standard care: -0.9 [5.9] points; $p = .001$). Notably, these results occurred despite the mHealth PR program not including an education program and incorporating only three essential components of PR. However, participants were able to monitor their symptoms, exercise and physical activity levels, and received weekly telephone support from a health care professional, suggesting that progress tracking and health coaching may be useful self-management tools to enhance general self-efficacy. By comparison, Jiang and colleagues [215] investigated an mHealth PR program that included both education and self-management interventions and results showed no

difference to centre-based PR for improvements in exercise self-efficacy, as measured by the Ex-SRES ($p = 0.14$). Interestingly, while centre-based PR participants received regular contact with health care professionals, those in the mHealth PR group did not. Instead, the mHealth PR app featured motivational tools and peer connectivity, which may have supported exercise self-efficacy to a similar extent to centre-based PR. From the limited evidence available, these findings suggest that mHealth PR programs incorporating self-management interventions and motivational tools may positively influence general and exercise self-efficacy. However, whether mHealth PR has a similar effect on other domains, such as emotional, social, or symptom-specific self-efficacy, remains unclear and warrants further investigation.

Adverse events

Seven randomised controlled trials [16, 17, 212-214, 217, 218] reported no serious adverse events related to the mHealth PR intervention, despite most participants having mild to very severe COPD and completing unsupervised exercise sessions of varying intensities. In addition, when compared to centre-based PR [16, 17], there were no differences in adverse events rates between groups (mHealth PR = 2; vs centre-based PR = 3). Adverse events that were unrelated to the mHealth PR intervention were identified in some trials [16, 213, 214, 217, 218], occurring in as high as 41% of participants in one trial [214] and highlighting the general condition of participants that were recruited to the studies. The findings suggest that mHealth PR is safe to deliver to people with COPD, regardless of disease severity.

Technological issues

Technological issues were reported in four randomised controlled trials [16, 17, 214, 217] and contributed to a small number of dropouts in three studies [17, 214, 217]. Notably, these three trials did not require participants to have prior experience with technology and provided participants with a tablet [17] or smartphone [214, 217] device to facilitate the mHealth PR programs. However, due to a lack of information from most trials, the true prevalence of technological issues in mHealth PR programs remains unclear, as does the potential influence of a participants' baseline digital literacy or familiarity with mobile devices. Based on the available evidence, technological issues did not appear to significantly affect clinical outcomes, though

future mHealth PR studies should report any technological challenges to enable more accurate interpretation of results.

Engagement

Some mHealth PR apps can measure engagement, characterised by any interaction with the app, by automatically tracking participant interactions through system-recorded data. For the purpose of interpreting clinical trial outcomes in mHealth PR participants, evaluations of mHealth PR app engagement trends have been best described in a randomised controlled trial [213] and an observational study [221]. Crooks and colleagues [213], determined a non-significant correlation between higher mHealth PR app usage and greater improvements in the CAT score, with a mean improvement in CAT score by -0.2 points (95% CI -0.7 to 0.3) for every seven-day increase in app use. The same mHealth PR app was evaluated in a long-term observational study [221] that found a trend towards reduced inpatient bed days and hospital admissions for highly engaged participants. The mHealth PR programs contained few essential components of PR which restricts the generalisability of these results to more comprehensive mHealth PR programs. However, these findings do highlight the importance of understanding app engagement behaviour of people with COPD when evaluating mHealth PR programs, a factor that has been largely unexplored in randomised controlled trials.

Three randomised controlled trials [212, 213, 218], a controlled clinical trial [223] and two observational studies [221, 225] have provided some insight into how people with COPD engage with mHealth PR apps. Overall mHealth PR app engagement, characterised by a participant accessing an app at least once, varied from 61% to 86% across six studies [212-214, 218, 221, 225]. A general decline in app engagement over time was found [16, 213, 214, 218]; a phenomenon that has been commonly described in other digital health technologies and is referred to as the 'law of attrition' [232]. Some studies [213, 214, 221, 223, 225] used system-recorded data to evaluate engagement with different mHealth PR app features and reported conflicting findings on whether people with COPD engaged more with the exercise components [214] or with the self-management components [221, 225]. Further research is needed to characterise app engagement behaviour of people with COPD to better understand the utility of different mHealth PR app features. The study in

Chapter 3 comprehensively evaluated engagement behaviour and adherence of people with COPD when using a multi-component mHealth PR app.

Adherence

Considering the heterogeneity of mHealth PR app features and PR program components, it is unsurprising that adherence to mHealth PR programs have varied significantly between studies, with exercise adherence rates ranging from 40% to 100% [16, 17, 212, 214, 217]. In two randomised controlled trials [214, 217], mHealth PR adherence rates were lower (41% to 62%) than those for home-based PR (84%) and centre-based PR (72%). Lower mHealth PR adherence may be partly explained by inconsistent adherence thresholds between the mHealth PR programs and the respective comparator PR program, as well as differences in communication with healthcare professionals. In a randomised controlled trial by Gloeckl and colleagues [214] participants in the home-based PR group received fortnightly motivational telephone calls to discuss the exercise program, whereas those in the mHealth PR group received motivation to use the app when app usage, rather than exercise adherence, fell below three days a week. The absence of regular, motivational health coaching that was focused on exercise progress may account for the significantly lower exercise adherence (41%) in the mHealth PR group. Likewise, in the study undertaken by Bourne and colleagues [16], mHealth PR participants who did not receive health coaching had lower adherence (62%) than centre-based PR participants (72%) who received regular face-to-face contact with healthcare professionals. In contrast, mHealth PR programs supported by regular motivational telephone calls [17, 212] or face-to-face sessions [217], achieved higher adherence rates (80% to 100%) [17, 212, 217]. These findings indicate that regular health coaching from a healthcare professional may be crucial in promoting high adherence to mHealth PR exercise programs.

However, the impact of motivational mHealth PR app features on adherence levels has yet to be fully examined. Few mHealth PR apps have included motivational features (see Table 5.5), such as displaying progress in graphs [212, 214] and loyalty rewards [215], with adherence rates varying between 41% and 80% [212, 214]. As was the case for Gloeckl and colleagues [214], substituting regular motivational telephone calls with a fully automated mHealth PR program may have negatively influenced adherence rates. However, it is unclear whether participants engaged with

certain motivational app features in the randomised controlled trials [212, 214, 215] or if this correlated with the adherence rates found. Further research is needed to evaluate the role that these features may have and whether people with COPD will engage with them. Engagement and adherence with a multi-component mHealth PR app which included motivational app features, such as in-app notifications and self-monitoring of exercise and daily goal progress, has been evaluated in the study in Chapter 3.

Economic and environmental impacts

To date there have been no randomised controlled trials that have evaluated the economic and environmental impact of an mHealth PR program. Committee members of the National Institute for Health and Care Excellence (NICE) medical technologies advisory committee in the UK critiqued a *de novo* model that was conducted by the developers of a commercially available mHealth PR app and reported potential cost-savings of £11,093 per PR service provider when the app was used to deliver mHealth PR to over 240 people with COPD per year [233]. The same committee conducted a cost-consequence and exploratory cost-effectiveness analyses of four commercially available mHealth PR apps and found potential cost-savings predominantly due to reduced staff time [234]. The committee members acknowledged considerable gaps in the literature that affected the results and highlighted the need for further research to investigate the effects of mHealth platforms on clinical outcomes, such as HRQOL and health status, and on resource usage costs. The study in Chapter 4 has evaluated the resource-usage costs and GHG emissions associated with an mHealth PR program when compared to centre-based PR.

AIMS OF THESIS

Despite several randomised controlled trials investigating the effects of mHealth PR, the strength of the evidence is underwhelming. Randomised controlled trials have been heterogenous in terms of study design and quality, mHealth PR app features and PR program components. Although there is some encouraging research that suggests that mHealth PR is safe and may be equivalent to centre-based PR for improvements in exercise capacity and health status, further research is required to make definitive conclusions on how mHealth PR effects clinical outcomes when compared to centre-based PR.

To date, no randomised controlled trial has rigorously investigated an mHealth PR program that contains all essential components of PR. Current understanding of how people with COPD engage with, and adhere to, mHealth PR programs remains poor and is crucial when interpreting effects on clinical outcomes. Additionally, there is a lack of knowledge of the resource usage costs and GHG emissions associated with mHealth PR when compared to centre-based PR. Therefore, the aims of this thesis were:

- i) To determine if mHealth PR is equivalent to centre-based PR for improvements in exercise capacity and health status in people with COPD;
- ii) To characterise the engagement behaviour and evaluate the adherence of people with COPD to the multiple components within an mHealth PR app; and
- iii) To determine the resource usage costs and carbon footprint of delivering an mHealth PR program to people with COPD.

CHAPTER TWO

MOBILE HEALTH PULMONARY REHABILITATION (m-PR): A RANDOMISED CONTROLLED EQUIVALENCE TRIAL

The following conference presentations and awards are based on the work in this chapter. A version of the manuscript has been submitted for publication as:

- **Brown, S.**, Wootton, S., Dale, M., Alison, J., Chan, A., Varnfield, M., Yang, I., Cunich, M., & McKeough, Z. Mobile Health Pulmonary Rehabilitation (m-PR): a Randomised Controlled Equivalence Trial. *Thorax* [submitted for publication and at revision stages].

CONFERENCE PRESENTATIONS

Brown, S. (2025, Sept 29). *Mobile health pulmonary rehabilitation (m-PR) compared to centre-based pulmonary rehabilitation in people with COPD: a randomised controlled equivalence trial.* [Accepted for Oral Presentation]. The European Respiratory Society International Congress 2025; September 27 – October 1 2025.

Brown, S. (2025, March 24). *Is mobile health pulmonary rehabilitation (m-PR™) equivalent to centre-based pulmonary rehabilitation for people with COPD? A randomised controlled equivalence trial.* [Oral Presentation]. TSANZSRS 2025 The Australia & New Zealand Society of Respiratory Science and The Thoracic Society of Australia and New Zealand (ANZSRS/TSANZ) Annual Scientific Meeting for Leaders in Lung Health & Respiratory Science; March 2025.

Brown, S. (2025, February 5). *Effectiveness of a pulmonary rehabilitation (m-PR™) program using mobile health (mHealth) technologies in people with chronic lung disease.* [Oral Presentation]. Digital Health and Informatics Network. Digital Health Week 2025; February 4-6 2025.

Brown, S. (2024, November 1). *Effects of a mobile health pulmonary rehabilitation program (m-PR™) compared to centre-based pulmonary rehabilitation on clinical outcomes in people with COPD.* [Oral Presentation]. The Thoracic Society of Australia and New Zealand NSW/ACT Branch Thoracic Clinical Update Day and ASM; November 1 2024.

AWARDS

Brown, S. (2024). Oral Session 2 Winner at The Thoracic Society of Australia and New Zealand NSW/ACT Branch Thoracic Clinical Update Day and ASM; November 1 2024, for oral presentation titled *Effects of a mobile health pulmonary rehabilitation program (m-PR™) compared to centre-based pulmonary rehabilitation on clinical outcomes in people with COPD.*

Brown, S. (2025). Ann Woolcock New Investigator Award – Finalist at The Australia & New Zealand Society of Respiratory Science and The Thoracic Society of Australia and New Zealand (ANZSRS/TSANZ) Annual Scientific Meeting for Leaders in Lung Health & Respiratory Science; March 24 2025, for oral presentation titled *Is mobile health pulmonary rehabilitation (m-PR™) equivalent to centre-based pulmonary rehabilitation for people with COPD? A randomised controlled equivalence trial.*

BACKGROUND

Pulmonary rehabilitation is strongly recommended as an effective, non-pharmacological intervention that improves exercise capacity, HRQoL and health status in people with COPD [3, 4, 23]. However, people with COPD globally experience barriers to access, uptake and completion of PR [4, 6]. PR is traditionally delivered as a supervised, group-based program conducted in a hospital or community centre and as such, barriers to PR attendance include transport availability, travel distance and program location [5]. Recent clinical practice guidelines [4] have recommended that people with COPD be given the option of telerehabilitation PR to overcome these barriers, with importance placed on maintaining safety and ensuring that the essential and desirable components of PR are provided [6, 192, 235].

mHealth, defined as the use of mobile devices to support public health [198], presents a novel mode of PR delivery. As summarised in the literature review in Chapter 1, home-based PR has been shown to be as effective as centre-based PR [179, 180] for improving clinical outcomes. Multi-component mHealth PR apps may facilitate the delivery of more comprehensive home-based PR programs, and the widespread availability and accessibility of mobile devices gives mHealth PR advantages over videoconferencing PR and web-based PR. Several studies have investigated the effects of mHealth PR with varied methodologies, from feasibility studies to randomised controlled trials [16, 17, 212-227]. There have been limitations with these studies, such as lacking randomisation [220, 223, 227], not comparing to centre-based PR [212-214, 216-219, 221, 222, 224-227], using outdated technology [217] and insufficient length of rehabilitation [219]. Some randomised controlled trials have compared mHealth PR to centre-based PR [16, 17, 215], and although some have had a low risk of bias [16, 215], these studies did not meet all essential components of PR [6]. Results from randomised controlled trials, as discussed in Chapter 1, have suggested that mHealth PR does not differ to centre-based PR in terms of improvements in exercise capacity [16, 17], health status [16, 215], HRQoL [16, 17, 215], and dyspnoea [16, 212, 215-218] and similarly does not improve physical activity [17, 212, 213], although more rigorous research is warranted.

The m-PR™ app is a new mHealth PR platform developed in Australia [236-238] for research purposes which can be used to deliver a PR program that includes all

essential and desirable PR components [6]. The m-PR™ app allows participants to complete endurance and resistance exercises, watch informational videos, track daily health goals, record symptoms, view a medication action plan and receive automated and customised motivational notifications. Example m-PR™ app screens are presented in Appendix 4 and a full-description of the m-PR™ app components can be found in Appendix 5. Previous evaluations [236, 238] of the m-PR™ app have shown that people with COPD find the m-PR™ app enjoyable, easy to use and helpful [238], and have detailed a rigorous development of the in-app notifications [236]. The primary aims of the current study were to determine if an mHealth PR program was equivalent to centre-based PR for improvements in exercise capacity and health status in people with COPD. Secondary aims were to: 1) determine if mHealth PR was equivalent to centre-based PR for improvements in HRQoL, dyspnoea and daily physical activity levels; 2) evaluate exercise session adherence levels; 3) assess participant acceptability and experience; and 4) compare the occurrence of adverse events between groups.

MATERIALS AND METHODS

Study design

This study was a prospective, single-blinded (assessor), multi-centre, equivalence, randomised controlled trial with concealed allocation. The protocol has been previously published [237].

Following baseline assessment and recruitment, participants were randomised using a real-time computer-generated random sequence in a 1:1 ratio to either the control (centre-based PR [CB-PR]) or intervention group (mHealth PR with m-PR™ app [m-PR]). Randomisation was stratified according to exercise capacity (6MWD < or \geq 400 m) and pulmonary function (FEV_1 < or \geq 40% predicted). This study was conducted and reported in accordance with the Consolidated Standards of Reporting Trials (CONSORT) guidelines [239]. The trial was approved by the Ethics Committee of the NSLHD and was registered with the Australian and New Zealand Clinical Trial Registry ACTRN12619001253190.

Participants

Participants were recruited between April 2022 and April 2024 following a comprehensive centre-based PR assessment at one of five sites in Sydney, New

South Wales (NSW), Australia. Participants were considered eligible if they were adults (aged ≥ 18 years) with a medical diagnosis of COPD (FEV_1 / forced vital capacity (FVC) ratio of < 0.7 ; $FEV_1 < 80\%$ predicted normal), had access to the internet via a smartphone or tablet (Android OS 7.0 or later or iOS 12.1 or later) and were willing to complete either centre-based PR or mHealth PR. Participants were excluded if they had an exacerbation of COPD in the two weeks prior to recruitment, had any comorbidities that could adversely affect performance during exercise assessments or training, were dependent on a mobility frame or had significant desaturation in oxygen levels (saturation of peripheral oxygen [SpO_2] $< 85\%$) on exertion. Participants were also excluded if they had participated in supervised exercise training in the 12 months prior, had limited English language skills that could impact the understanding of the m-PR™ app or if they had any limitations to the use of technology (e.g. irreversible vision impairment, cognitive impairment). Written informed consent was obtained from all participants.

Intervention group

Participants randomised to the m-PR group had one home-based visit where they were assisted in downloading the m-PR™ app onto their smartphone or tablet and were provided with a 30-minute education session on the use of the app and how to complete their prescribed exercises safely at home, together with a hard-copy instruction manual. The m-PR™ app included various app features, such as an exercise program, informational videos, daily goal settings, symptom monitoring questionnaires, a medication action plan, motivational in-app notifications (customised by computer-generated algorithm) and self-monitoring of all recorded data in graphical or list format. The m-PR™ app contained both the participant-facing app and a clinician web-based portal that allowed the physiotherapist to tailor the m-PR™ app interventions to the participant and monitor engagement and adherence. The interplay between the participants, physiotherapist and m-PR™ app is summarised in Figure 2.1. Figures of the m-PR™ app screens are presented in Appendix 4, a detailed summary of the m-PR™ app program components are presented in Appendix 5 and a list of the informational videos are presented in Appendix 6. The essential and desirable components of PR [6] included in the mHealth PR program are summarised in Figure 2.2.

Participants in the m-PR group had one week to familiarise themselves with the m-PR™ app before undertaking eight weeks of unsupervised, mHealth PR. Each week, participants were given several tasks to complete through the m-PR™ app, including three exercise sessions (the completed Consensus on Exercise Reporting Template presented in Appendix 7 describes the exercise protocol), informational videos and symptom questionnaires. Referral to a multi-disciplinary team healthcare professional was made if appropriate (Appendix 7). All participants were given an activity tracker (Fitbit Inspire, Fitbit Inc, San Francisco, US) and had the option to receive daily step goals and weekly physical activity coaching. Programs were extended by up to four weeks if participants were medically unwell, if they had medical appointments or procedures, or if there were public holiday periods impacting participation. Health coaching was provided through in-app notifications and weekly telephone calls with a physiotherapist.



Figure 2.1. m-PR™ app features and process. Features of the multi-component m-PR™ app. m-PR™ app process includes participants interacting with the m-PR™ app and communicating with the physiotherapist through telephone calls, physiotherapists customising the m-PR™ app through the web-based portal and monitoring participant engagement and adherence, and automated synchrony between the web-based PR platform and the m-PR™ app.

Essential Components	Desirable Components	
✓ Initial centre-based assessment by a HCP	✓ Anxiety and depression assessment	✓ Centre-based assessment at discharge by HCP
✓ Exercise test at the time of assessment	✓ Inhaler technique assessment	✓ Delivery of alternative PR model to increase program access
✓ Field exercise test	✓ Assessment of comorbidities	✓ Shared decision making between participant and HCP
✓ Quality of life measure	✓ Upper limb training	✓ Program delivered in a non-hospital setting
✓ Dyspnoea assessment	✓ Structured education	✓ Regular contact between HCP and participant
✓ Nutritional status evaluation	✓ Individualised education	✓ HCP with expertise in exercise for comorbid participants
✓ Occupational Status evaluation	✓ Self-management training	✓ Evidence of efficacy
✓ Endurance training	✓ Goal setting	✓ Evidence of effectiveness
✓ Resistance training	✓ Physical activity counselling	✓ HCP trained to deliver digital solutions if used
✓ Exercise program individually prescribed	✓ Smoking cessation support	✓ Documented standard operating procedure
✓ Exercise program individually progressed	✓ Individualised action plan	
✓ HCP with experience in exercise prescription and progression	✓ Home exercise program	
✓ HCP trained to deliver components of the PR model	✓ Maintenance exercise training	

Figure 2.2. The essential and desirable components of the mHealth PR program. The essential and desirable components of PR, as identified by Holland et al [6], that were delivered in an mHealth PR program that used the m-PR™ app. Airway clearance technique for bronchiectasis and cystic fibrosis were excluded from desirable components as not relevant to COPD. HCP: healthcare professional.

Control group

Participants randomised to the CB-PR group attended two sessions per week of supervised, group-based PR for eight weeks, reflecting typical PR structure in Australia [3], and included the same exercise protocol as the m-PR group (Appendix 7). All participants were given a hard copy exercise diary and encouraged to complete one unsupervised, home-based exercise session per week. Self-management education was provided as needed during supervised sessions with the physiotherapists or a multi-disciplinary team healthcare professional (Appendix 7). Participants were offered to attend weekly group-based face-to-face education sessions with a physiotherapist or another member of the multidisciplinary team when available. Weekly education sessions were not available to all participants

throughout the trial period due to the impact of COVID-19 pandemic restrictions. Programs could be extended for up to four weeks for the same reasons as the m-PR group.

Outcome measures

Participants completed outcomes during centre-based assessments at baseline and end-intervention and an assessor blinded to group allocation conducted the end-intervention assessment.

Primary Outcome Measures

Functional exercise capacity and health status were measured as co-primary outcomes. Change in functional exercise capacity was measured by the 6MWD in metres, obtained from the 6MWT. Standardised instructions were provided according to protocol [7], involving participants walking as far as possible in six minutes, with greater distances achieved indicating greater exercise capacity. Two tests were performed at baseline and at end-intervention on either a 15 m or 20 m walking track, dependent on PR recruitment site, and the best of two 6MWT was recorded. Pulse rate and SpO₂ were monitored during the 6MWT using a pulse oximeter (RAD-5v, Masimo Corporation, Irvine, California, USA) and dyspnoea and rate of perceived exertion were recorded before and after each 6MWT using the modified 0 – 10 Borg dyspnoea scale [87].

Health status was measured using the total score from the CAT questionnaire [97]. This is a self-administered, eight-item questionnaire that asks people with COPD to rate, on a 5-point Likert scale, the impact of cough, mucus, chest tightness, breathlessness on hills and stairs, limitations with household activities of daily living, sleep and fatigue. The questionnaire provides a score out of 40, with higher scores indicating a negative impact on health status.

Secondary Outcome Measures

Secondary outcome measures included change in HRQoL (SGRQ), dyspnoea (mMRC), daily physical activity, participant experiences and satisfaction, app usability and quality, and rates of exercise session adherence and adverse events.

All participants completed a custom-designed technology skills questionnaire at baseline only that evaluated self-rated technology skills using mobile devices.

Participants rated their skills on a six-point Likert scale ranging from Very Poor (0) to Very Good (6).

Changes in HRQoL were measured using the SGRQ, which is a self-administered 53-item questionnaire that evaluates the impact of respiratory disease across three domains: symptoms, activity limitations and impact of disease. A total score is calculated from the three domains, with higher scores indicating worse HRQoL.

Dyspnoea severity was determined through the mMRC scale [92], which allows participants to rate how breathlessness affects their daily physical activity on a staged scale ranging from zero to four. A higher score indicates more severe dyspnoea.

Physical activity levels were measured using the ActivPAL4 activity monitor (PAL Technologies Ltd, Glasgow, UK), which is a small, medical-grade, tri-axial accelerometer that has been validated for the measurement of physical activity in people with COPD [240]. The device was attached to the participant's thigh using a waterproof adhesive dressing and worn for 24 hours a day, for seven days at baseline and in the seven days following program completion. At least four valid days were used for analysis, with physical activity levels reported as daily step count, time spent in MVPA and low-intensity physical activity (LPA).

Participant experiences and satisfaction were measured at end-intervention using a custom-designed satisfaction survey and the Physical Activity Enjoyment Scale (PACES) [240]. The custom-designed survey asked participants to rate, on a five-point Likert scale, their overall experience and satisfaction with respective PR programs, and whether they found the program helpful for motivation to exercise and increase physical activity, understanding management of disease, and smoking cessation if relevant. In addition, the participants in the m-PR group were asked to rate how easy, helpful and important the different m-PR™ app features and communication with the physiotherapist were. The PACES questionnaire [241] is a self-administered, 18-item questionnaire that asks participants to rate, on a seven-point Likert scale, levels of enjoyment with their respective PR program. A total score is calculated out of a possible 126 points, with higher scores indicating higher enjoyment.

Experience with m-PR™ app usability and quality was evaluated in the m-PR group only, using the System Usability Scale (SUS) [242] and the Mobile Application Rating Scale: User version (u-MARS) [243], respectively. The SUS is a self-administered, 10-item questionnaire where participants answer, on a five-point Likert scale, whether they agree or disagree with statements regarding usability of the m-PR™ app. m-PR™ app usability was deemed acceptable if the mean SUS score was above 70 points [242]. The u-MARS questionnaire is a self-administered questionnaire which is designed to capture participant perceptions of the quality of the m-PR™ app in regard to engagement, functionality, aesthetics, information quality and subjective quality. Questions are presented as five-point Likert scales and a total score is provided with a score of five being the highest and indicating better app quality.

A qualitative analysis of participant experiences with the m-PR and CB-PR programs has been published separately [244] and is not part of the body of work within this thesis.

A priori adherence rates were compared between groups. Participants were considered adherent if they attempted $\geq 70\%$ of their prescribed exercise sessions [6]. Prescribed sessions were three sessions a week for the m-PR group and two sessions a week for the CB-PR group. Completion of the exercise diary was not monitored by staff and therefore adherence to the home-based exercise sessions in the CB-PR group was analysed separately. Completion of PR was considered if participants completed at least one co-primary outcome measure at end-intervention.

Adverse events were compared between groups and were classified as either related or unrelated to the study, and as either serious or mild [245]. Adverse events were considered serious if an event resulted in death, was life-threatening, resulted in inpatient hospitalisation or significant incapacity, or interfered substantially with normal life function.

Analysis

Sample size calculations were determined by assuming no difference between groups and a SD of 56 m for 6MWD [246] or a SD of 7 for total CAT score [8]. A total of 88 participants were required to ensure that the lower 95% confidence interval (CI) bound for the mean difference in 6MWD to be no more than 30 m for 6MWD. For the

CAT score, 86 participants were required to ensure the lower 95% CI bound for the mean difference did not exceed 3.8 points. Accounting for a 15% dropout rate on the larger sample size of 88 participants, a total of 100 participants were targeted for recruitment.

Statistical analyses were conducted using SPSS Statistics (V.29.0; IBM Corp, New York, USA). All data were analysed using an ITT and a per-protocol analysis. Per-protocol analyses included participants who were adherent as defined above. Normality was tested using the Shapiro-Wilk test with visual inspection of histograms and qq-plots. A logistic regression analysis was used to compare baseline characteristics and baseline outcome data of those with and without missing data. Given no significant differences were found, missing data were considered missing at random, and imputation of missing data was not performed.

Differences between groups over time were estimated using the two one-sided test (90% CI) through linear mixed models, with data presented as the mean difference and 95% CI and results for the co-primary endpoints were adjusted for multiple testing using Bonferroni's method. Equivalence margins were set based on the MCID for each outcome. For the primary outcomes, an equivalence margin of ± 30 m was used for 6MWD [7] and ± 2 points for CAT score [8]. Equivalence margins of ± 4 points, ± 0.5 points and ± 1100 steps/day were set for the SGRQ Total score [247], mMRC score [248] and daily step count [249]. Between-group differences in technology skills, satisfaction, enjoyment and rates of MCID achievement, adherence and AE were analysed using the student's t-test for continuous variables and the chi-square test for categorical variables. The odds for MCID achievement and positive participant experience were determined using two-way contingency tables and results for the co-primary endpoints adjusted using Bonferroni's method. Baseline characteristics and results for PACES, u-MARS and SUS were presented as mean and SD for normally distributed data, or medians and IQR for non-normally distributed data.

RESULTS

Participant flow and completion rates are summarised in Figure 2.3. A total of 90 participants were randomised with baseline characteristics presented in Table 2.1. Recruitment included 10 participants fewer than the intended sample size due to PR site closures during the COVID-19 pandemic. Participant mean (SD) age was 75 (7)

years with all participants having at least one comorbidity. Most participants had moderate (n = 60 [67%]) or severe (n = 26 [90%]) COPD and rated at least adequate for self-rated technology skills (n = 80 [91%]). Eighty participants (m-PR: n = 38; vs CB-PR: n = 42) completed at least one primary outcome measure at end-intervention. A total of 68 participants (m-PR: n = 32; vs CB-PR n = 36) were included in the per-protocol analyses. A comparison of ITT, per-protocol and drop out baseline characteristics have been summarised in Appendix 8.

Nine (24%) m-PR participants had access to a treadmill and eight (21%) had access to a stationary cycle. Thirty-six (95%) m-PR participants were prescribed ground-based walking as part of their program. Thirty-nine (93%) and 41 (98%) CB-PR participants were prescribed exercises on the treadmill and stationary cycle, respectively. Seven (17%) participants were prescribed ground-based walking for at least one centre-based session. All CB-PR participants were prescribed ground-based walking for their unsupervised home-based exercise session. Twenty-six (69%) of the 38 m-PR participants chose to receive daily step goals during their PR program across a mean (SD) duration of 4 (1.8) weeks.

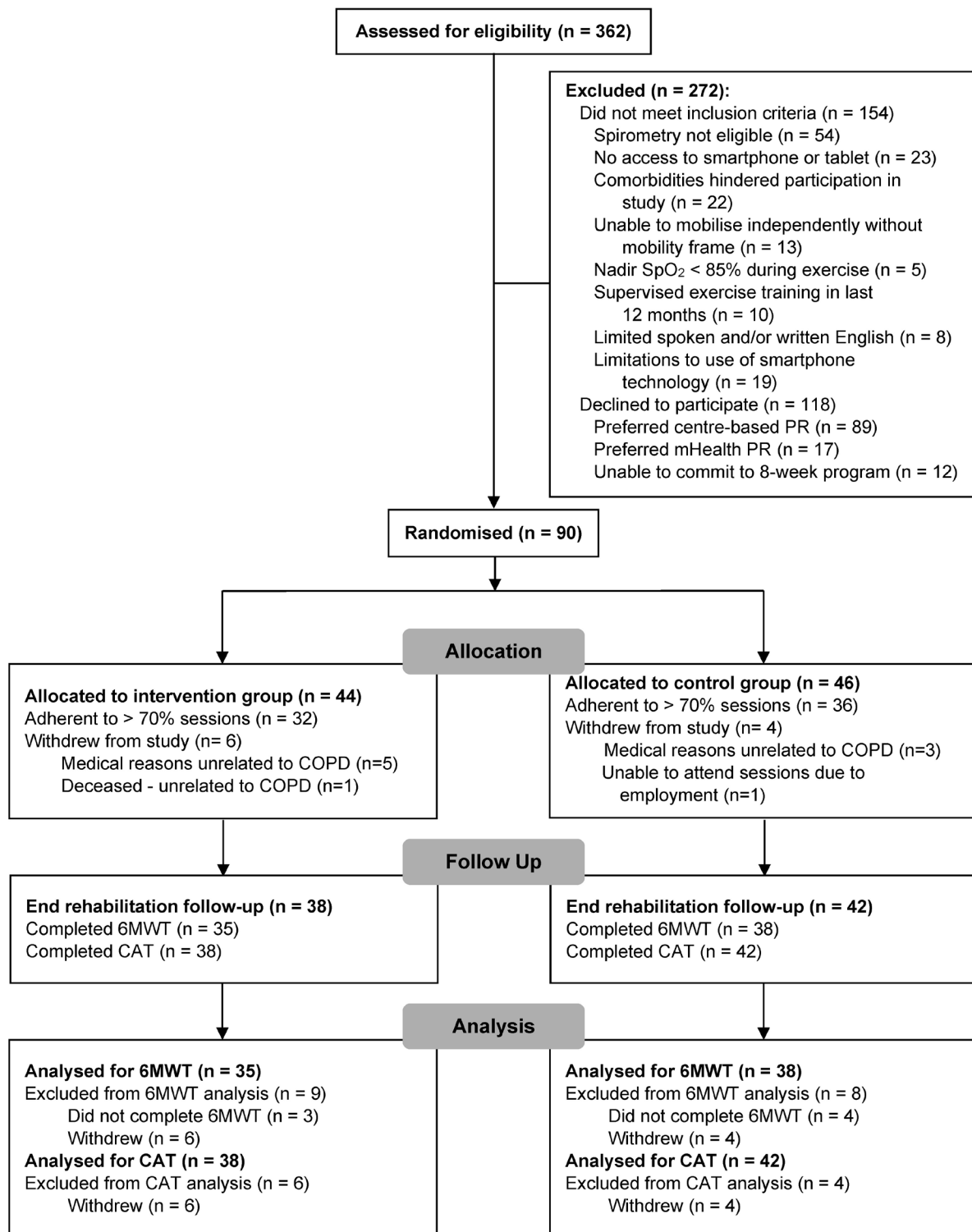


Figure 2.3. Consort flow diagram. Flow of study participants through the trial. 6MWT: six-minute walk test; CAT: COPD Assessment Test; COPD: Chronic obstructive pulmonary disease; PR: pulmonary rehabilitation; SpO₂: saturation of peripheral oxygen.

Table 2.1. Baseline participant characteristics.

Characteristics	m-PR	CB-PR
Participants, n	44	46
Age, years	75 (7)	75 (6)
Sex, female, n (%)	21 (48)	27 (59)
Height, m	1.7 (0.1)	1.7 (0.1)
Weight, kg	79 (17)	74 (19)
BMI, kg/m ²	27 (5)	26 (6)
Preferred language, English, n (%)	42 (95)	45 (98)
Smoking status, n (%)		
Non-smoker	5 (11)	2 (4)
Current smoker	7 (16)	11 (24)
Ex-smoker	32 (73)	33 (72)
Smoking history, pack-years*	32 (27)	36 (23)
Employment status, n (%)		
Employed	6 (14)	3 (7)
Not working	38 (86)	43 (93)
LTOT, n (%)	0 (0)	1 (2)
Pulmonary function		
FEV ₁ L	1.45 (0.47)	1.35 (0.49)
FEV ₁ % predicted	58 (15)	55 (14)
FVC L	2.89 (0.84)	2.71 (1.02)
FVC % predicted	86 (19)	84 (19)
FEV ₁ /FVC %	51 (11)	51 (10)
Severity of COPD, n (%)		
GOLD I	1 (2)	0 (0)
GOLD II	29 (66)	31 (67)
GOLD III	12 (27)	14 (30)
GOLD IV	2 (5)	1 (2)
Comorbidities, n (%) [^]		
Presence of any comorbidity	44 (100)	46 (100)
Cancer	14 (32)	21 (46)
Cardiovascular	35 (80)	33 (72)
Mental	6 (14)	12 (26)
Metabolic	15 (34)	17 (37)
Musculoskeletal	22 (50)	31 (67)
Respiratory	13 (30)	16 (35)
Other	31 (71)	32 (70)
Respiratory medications [^]		
Short-acting bronchodilator	28 (64)	27 (59)
Long-acting bronchodilator	14 (32)	23 (50)
Inhaled corticosteroid	5 (11)	4 (9)
Combined therapy	32 (73)	32 (71)
Oral antibiotics	0 (0)	2 (4)
Oral corticosteroids	3 (7)	3 (7)
Technology skills (adequate or better) [#] , n (%)	39 (91)	41 (91)

Values are presented as mean (SD) unless otherwise stated. Technology skills were assessed through a custom-designed questionnaire where participants rated their overall technology skills on a 6-point Likert scale from 'Very Poor' to 'Very Good'. *Smoking history available for n = 83 (m-PR = 39 and CB-PR = 44); [^]Multiple responses possible; [#]Missing technology skills data n = 2 (m-PR = 1, CB-PR = 1) BMI: body mass index; CB-PR: centre-based pulmonary rehabilitation group; FEV₁: forced expiratory volume in 1 s; FEV₁/FVC: FEV₁ as a percentage of forced vital capacity; FVC: forced vital capacity; GOLD: Global Initiative for Chronic Obstructive Lung Disease; kg: kilogram; LTOT: long term oxygen therapy; m-PR: mobile pulmonary rehabilitation group.

Primary Outcomes

There were no between-group differences in 6MWD (Table 2.2); however, the upper bound of the CI exceeded the equivalence margin and superiority of the m-PR group could not be excluded (Figure 2.4a). Similarly, when compared to the CB-PR group, the odds of reaching the MCID for the 6MWD was no different in the m-PR group (Table 2.3). A significant between-group difference in the CAT score favoured the m-PR group (Table 2.2), with lower and upper limits of the CI exceeding equivalence margins, indicating superiority (Figure 2.4b). When compared to the CB-PR group, the odds of reaching the MCID on the CAT was 4.8 times higher in the m-PR group (Table 2.3).

Secondary Outcomes

There were no significant between-group differences in SGRQ, mMRC and daily step count (Table 2.2). Equivalence was found for SGRQ, mMRC and physical activity levels (Figure 2.4c-e), however the lower bound of the CI for the SGRQ Total score, and the upper bound for daily step count, exceeded equivalence margins and therefore superiority of the m-PR group could not be excluded for these outcomes (Figure 2.4c, Figure 2.4e).

The per-protocol analyses demonstrated similar within-group and between-group mean differences for all outcome measures when compared to the ITT analyses (Table 2.4, Figure 2.4).

Participants in both groups rated high levels of enjoyment with their rehabilitation programs (mean [SD] PACES score, m-PR: 103.5 [18] points; vs CB-PR: 96 [25] points). The odds of perceiving that the PR program was helpful in disease management were significantly higher in the m-PR group (Table 2.5). Overall m-PR™ app usability achieved acceptability (SUS score median [IQR], 87.5 [22.5] points) and mean [SD] overall u-MARS score was 4.0 [0.5] points out of a possible score of five. All m-PR participants found the exercises and communication with the physiotherapist important (Table 2.6).

Adherence results, program duration and reasons for missed sessions are summarised in Table 2.7. There was no difference in adherence between groups. Only six (14%) participants in the CB-PR group completed their home exercise diary, attempting a mean (SD) of 7 (2) sessions.

There was no serious AE related to the study (Table 2.8). Minor technological issues occurred with the m-PR™ app that were able to be resolved remotely. One participant had technological issues with the m-PR™ app which required a home-visit to resolve.

Table 2.2. Clinical Outcomes: intention-to-treat analysis (n = 90).

	Baseline		Study completion		Within-group		Between-group (m-PR minus CB-PR)
	m-PR	CB-PR	m-PR	CB-PR	m-PR	CB-PR	
6MWD , metres	414 (85)	431 (91)	458 (76)	445 (89)	28 (15 to 42)*	16 (3 to 29)*	13 (-6 to 31) [†]
CAT , point	17 (8)	17 (6)	13 (7)	17 (6)	-4.4 (-6.1 to -2.8)*	-0.5 (-1.1 to 2.0)	-4.9 (-7.2 to -2.6)* [‡]
SGRQ , point							
Symptom	51 (23)	51 (24)	43 (26)	47 (23)	-8.4 (-13.1 to -3.8)*	-6.3 (-10.8 to -1.9)*	-2.1 (-8.6 to 4.4)
Activity	58 (18)	61 (18)	53 (21)	57 (19)	-4.4 (-8.1 to -0.7)*	-2.4 (-5.8 to 1.1)	-2.1 (-7.1 to 3.0)
Impact	25 (17)	29 (17)	21 (18)	24 (16)	-4.8 (-7.4 to -2.2)*	-4.8 (-7.3 to -2.3)*	0 (-3.7 to 3.7)
Total	39 (16)	42 (16)	34 (18)	38 (16)	-5.3 (-7.7 to -2.9)*	-4.3 (-6.6 to -2.0)*	-1.0 (-4.3 to 2.4) [^]
mMRC , point	2 (1)	2 (1)	1 (1)	1 (1)	-0.4 (-0.6 to -0.2)*	-0.2 (-0.4 to 0)*	-0.2 (-0.5 to 0.1) [#]
Physical activity							
Daily steps , count	4835 (2436)	4741 (1971)	5595 (2217)	4641 (1985)	688 (239 to 1137)*	111 (-300 to 521)	577 (-31 to 1185) [†]
LPA/day , mins	57 (29)	56 (23)	61 (24)	53 (21)	5.6 (1.1 to 10.1)*	-1.5 (-5.6 to 2.6)	7.1 (1.0 to 13.2)*
MVPA/day , mins	8 (9)	8 (8)	12 (11)	10 (11)	3.1 (0.6 to 5.6)*	2.4 (0.2 to 4.7)*	0.7 (-2.7 to 4.1)

Data are presented as unadjusted mean (SD) or mean difference (95% CI) adjusted for baseline results and results for 6MWD and CAT were corrected using Bonferroni method. Statistical significance of within-group and between-group mean differences determined through linear mixed model analysis.

*Statistically significant within-group or between-group differences.

[†]CI exceeds the upper equivalence margin and cannot exclude superiority of m-PR.

[‡]CI upper and lower ends exceed the lower equivalence margin and indicates superiority of m-PR.

[^]CI exceeds the lower equivalence margin and cannot exclude superiority of m-PR.

[#]CI upper and lower ends fall within both ends of the equivalence margins and indicate equivalence.

6MWD: six-minute walk distance; CAT: COPD Assessment Test; CB-PR: centre-based pulmonary rehabilitation group; LPA: light intensity physical activity; mins: minutes; mMRC: modified Medical Research Council dyspnoea scale; m-PR: mobile pulmonary rehabilitation group; MVPA: moderate to vigorous intensity physical activity; SGRQ: St George's Respiratory Questionnaire.

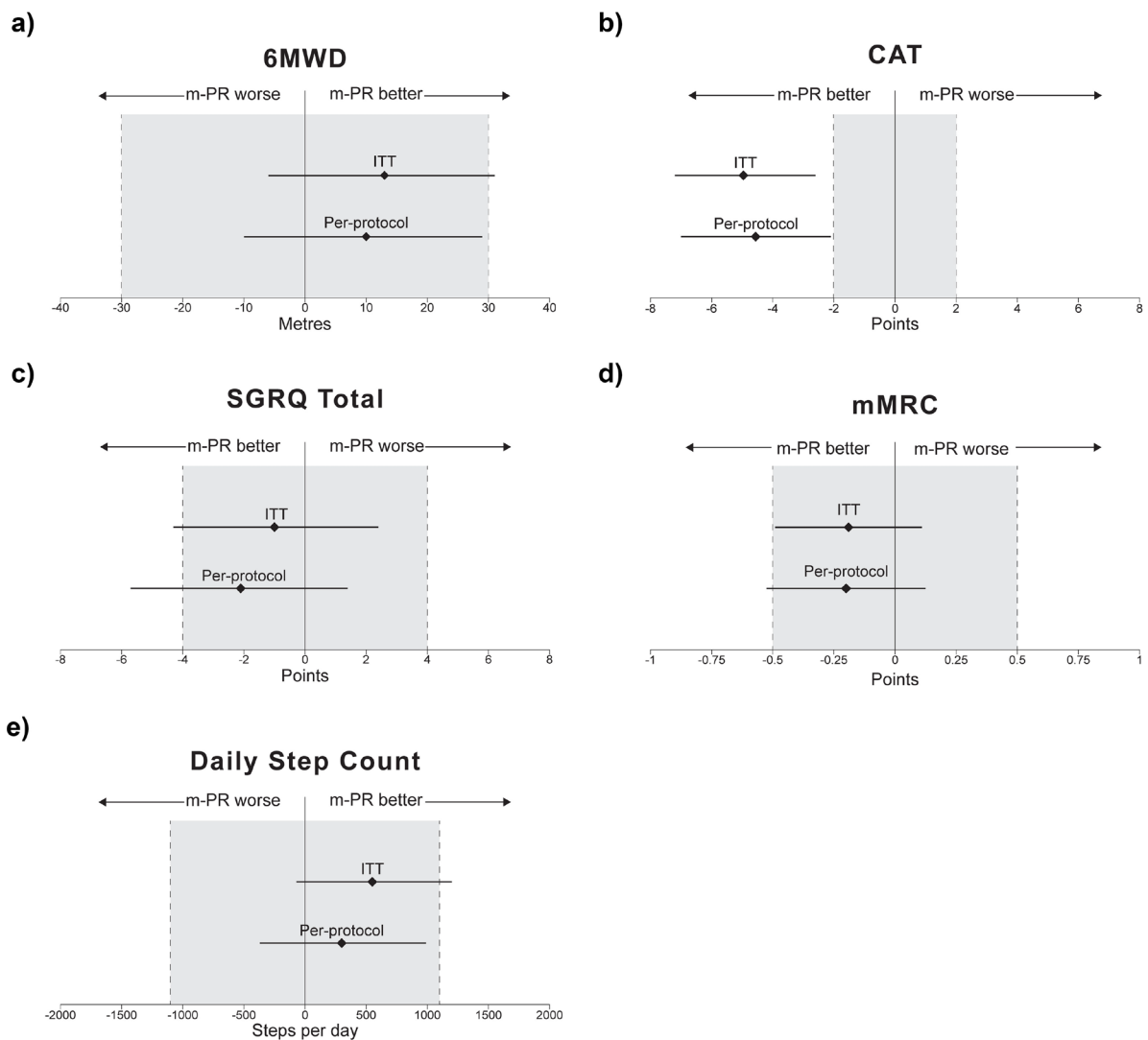


Figure 2.4a-e. Differences between groups and equivalence margins. ITT and per-protocol differences between groups and equivalence margins for a) 6MWD, b) CAT, c) SGRQ Total; d) mMRC; e) daily step count. 6MWD: six-minute walk distance; CAT: COPD Assessment Test; ITT: intention-to-treat; mMRC: modified Medical Research Council dyspnoea scale; m-PR: mobile pulmonary rehabilitation group; SGRQ: St George’s Respiratory Questionnaire.

Table 2.3. Proportion of participants with complete data who achieved MCID.

	Participants (completers), n		MCID achieved		Odds Ratio (95% CI)	p-value
	m-PR	CB-PR	m-PR	CB-PR		
6MWD	35	38	10 (29)	15 (39)	0.6 (0.2 to 1.6)	0.33
CAT	38	42	26 (68)	13 (31)	4.8 (1.9 to 12.5)	<0.001*
SGRQ (Total)	38	42	19 (50)	19 (45)	1.2 (0.5 to 2.9)	0.67
Physical activity	29	35				
Daily step count			12 (41)	7 (20)	2.8 (0.9 to 8.6)	0.06

Data are presented as n (%) or odds ratio (95% CI). Statistical significance determined through chi-square test with results for 6MWD and CAT corrected using Bonferroni method. The proportion of participants is relevant to the number of participants who had complete data sets for that outcome measure.

*Statistically significant (p < 0.025).

6MWD: six-minute walk distance; CAT: COPD Assessment Test; CB-PR: centre-based pulmonary rehabilitation group; MCID: minimum clinically important difference; m-PR: mobile pulmonary rehabilitation group; SGRQ: St George's Respiratory Questionnaire.

Table 2.4. Clinical Outcomes: per-protocol analysis.

	Participants, n		Baseline		Study completion		Within-group		Between-group m-PR minus CB-PR
	m-PR	CB-PR	m-PR	CB-PR	m-PR	CB-PR	m-PR	CB-PR	
6MWD , metres	30	36	422 (76)	423 (83)	451 (67)	439 (88)	26 (12 to 41)*	16 (3 to 30)*	10 (-10 to 29) [†]
CAT , point	32	36	17 (8)	17 (6)	12 (7)	17 (6)	-4.8 (-6.6 to -3.0)*	-0.2 (-1.9 to 1.5)	-4.6 (-7.1 to -2.2)* [‡]
SGRQ , point	32	36							
Symptom			49 (23)	54 (24)	39 (24)	47 (23)	-10.1 (-14.9 to -5.3)*	-7.1 (-11.7 to -2.6)*	-3.0 (-9.6 to 3.7)
Activity			57 (18)	60 (19)	53 (21)	58 (20)	-4.8 (-9.0 to -0.7)*	-1.1 (-5.1 to 2.8)	-3.7 (-9.4 to 2.0)
Impact			26 (19)	29 (17)	20 (18)	25 (17)	-5.4 (-8.3 to -2.5)*	-4.4 (-7.2 to -1.7)*	-1.0 (-5.0 to 3.1)
Total			39 (17)	43 (17)	33 (18)	39 (17)	-6.0 (-8.6 to -3.4)*	-3.9 (-6.3 to -1.5)*	-2.1 (-5.7 to 1.4) [^]
mMRC , point	32	36	2 (1)	2 (1)	1 (1)	1 (1)	-0.4 (-0.6 to -0.2)*	-0.2 (-0.4 to 0)	-0.2 (-0.5 to 0.1) [^]
Physical activity	27	32							
Daily steps , count			5307 (2488)	4597 (1874)	5616 (2043)	4702 (1976)	533 (56 to 1010)*	256 (-176 to 687)	277 (-366 to 920) [†]
LPA/day , mins			61 (30)	56 (24)	60 (20)	54 (21)	3.7 (-0.9 to 8.4)	-0.6 (-4.8 to 3.7)	4.3 (-2.0 to 10.6)
MVPA/day , mins			10 (10)	6 (6)	13 (11)	9 (11)	2.8 (-0.1 to 5.6)	3.3 (0.8 to 5.9)*	-0.6 (-4.4 to 3.2)

Data are presented as adjusted mean (SD) or mean difference (95% CI) adjusted for baseline data and results for 6MWD and CAT were corrected using Bonferroni method. Statistical significance of within-group and between-group mean differences determined through linear mixed model analysis. Participants (n) represent the number of participants who completed an outcome measure at end-intervention.

*Statistically significant within-group or between-group differences.

[†]CI upper and lower ends fall within both ends of the equivalence limits and indicate equivalence.

[‡]CI upper and lower ends fall above the lower equivalence limit and indicates superiority of m-PR.

[^]CI exceeds the lower equivalence limit and cannot exclude superiority of m-PR.

6MWD: six-minute walk distance; CB-PR: centre-based pulmonary rehabilitation group; CAT: COPD Assessment Test; LPA: light intensity physical activity; mins: minutes; mMRC: modified Medical Research Council dyspnoea scale; m-PR: mobile pulmonary rehabilitation group; MVPA: moderate-vigorous intensity physical activity; SGRQ: St George's Respiratory Questionnaire.

Table 2.5. Participant experiences with m-PR and CB-PR programs.

	m-PR	CB-PR	Odds Ratio (95% CI)
Overall, how beneficial was your PR program, at least moderately beneficial	37 (97)	39 (93)	2.9 (0.3 to 28.6)
How easy was it for you to participate in your PR program, at least somewhat easy	31 (82)	31 (74)	1.6 (0.5 to 4.6)
Overall, how would you rate the care you received during your PR program, at least good	38 (100)	40 (95)	4.8 (0.2 to 102)
How helpful did you think your PR program was at improving, at least somewhat helpful:			
Your motivation to exercise	37 (97)	36 (86)	6.2 (0.7 to 53.8)
Your motivation to take more steps each day	37 (97)	33 (79)	10.1 (1.2 to 84)*
Your understanding about how to manage your lung condition (e.g. breathlessness)	36 (95)	28 (67)	9 (1.9 to 42.9)*
Your ability to monitor your symptoms	33 (87)	28 (67)	3.3 (1.1 to 10.3)*
Your ability to manage your symptoms during flare up	30 (79)	23 (55)	3.1 (1.2 to 8.3)*
Your ability to engage in smoking cessation (if relevant)	7 (64)	7 (50)	1.8 (0.3 to 8.8)
Did you have enough time to discuss your COPD disease management with the health professional during your PR program, yes	31 (82)	28 (67)	2.2 (0.8 to 6.3)
Did you understand the plan for your PR program, yes	37 (98)	34 (81)	8.7 (1.0 to 73.3)*

Data presented as n (%). Odds ratio and statistical significance determined through chi-square test.
 *Statistically significant (p < 0.05)
 CB-PR: centre-based pulmonary rehabilitation group; COPD: chronic obstructive pulmonary disease; m-PR: mobile pulmonary rehabilitation group; PR: pulmonary rehabilitation.

Table 2.6. m-PR participant experiences with the m-PR app components.

	Phrase of the day	Smiley face slider	Symptom monitoring	Exercise sessions	Exercise videos	Educational videos	Goal setting (e.g. steps)	Action plan (if applicable)	Communicating with therapist	m-PR™ app notifications
Somewhat easy or very easy	N/A	35 (92)	29 (88)	33 (89)	34 (90)	31 (89)	30 (81)	23 (92)	37 (97)	32 (87)
Somewhat helpful or very helpful	N/A	33 (87)	32 (87)	35 (95)	36 (95)	30 (81)	28 (82)	20 (83)	37 (97)	35 (92)
Somewhat important or very important	17 (50)	25 (68)	29 (76)	38 (100)	35 (92)	32 (87)	32 (89)	21 (84)	38 (100)	30 (86)

Data presented as n (%). The number of responders to each question differed and is as follows:

- Total number of responders to “ease of use” component: symptom monitoring (n = 33), exercise session (n = 37), educational videos (n = 35), goal setting (n = 37), action plan (n = 25), notifications (n = 37), how are you today, exercise videos and communication with therapist (n = 38)
- Total number of responders to “helpfulness” component: symptom monitoring (n = 37), exercise session (n = 37), educational videos (n = 37), goal setting (n = 34), action plan (n = 22), how are you today, exercise videos, communication with therapist and notifications (n = 38)
- Total number of responders to “importance” component: phrase of the day (n = 34), how are you today (n = 37), educational videos (n = 37), goal setting (n = 36), action plan (n = 25), notifications (n = 35), symptom monitoring, exercise sessions, exercise videos and communication with therapist (n = 38)

COPD: chronic obstructive pulmonary disease; m-PR: mobile pulmonary rehabilitation; PR: pulmonary rehabilitation; N/A: not applicable.

Table 2.7. Participant exercise session adherence and program length.

	m-PR	CB-PR
Number of participants (excluding dropouts), n	38	42
Number of participants (completed at least one primary outcome), n (%)	38 (100)	42 (100)
Number of sessions attempted, mean (SD)	21 (6)	14 (4)
Proportion of sessions attempted, mean (SD)	86 (23)	87 (23)
Number of participants adherent to exercises, n (%)	32 (84)	36 (86)
Number of participants given physical activity goals, n	26	N/A
Number of participants adherent to physical activity goals, n (%)	13 (50)	N/A
Number of participants requiring extension of program, n (%)	26 (68)*	37 (88)
Length of program (weeks)	10 (2)	10 (2)
Length of extension provided, weeks, mean (SD)	2 (2)	2 (2)
Reason for missed session, n (%)[†]		
Medically unwell	25 (66)*	17 (41)
Medical appointment or procedure	3 (8)	5 (12)
Public holiday period	1(3)*	19 (45)
Work or social commitment	0 (0)*	7 (17)
Unspecified	0 (0)*	16 (38)

Results presented as mean (SD) or n (%). Results reported for intention-to-treat population. Number of sessions prescribed differed between groups (m-PR = 24 sessions vs CB-PR = 16 sessions) as the home-based session for the CB-PR was not included. Participants considered adherent if they attempted > 70% of prescribed sessions. Statistical significance for mean (SD) determined through student's t-test. Statistical significance for n (%) determined through chi-square test.

*Statistically significant (p < 0.05)

[†]Multiple responses possible

CB-PR: centre-based pulmonary rehabilitation group; m-PR: mobile pulmonary rehabilitation group; N/A: not applicable.

Table 2.8. Adverse events.

	Completers		
	m-PR	CB-PR	Drop out
Participants, n	38	42	10
Adverse events related to trial, n (%)			
Serious	0 (0)	0 (0)	0 (0)
Minor	7 (18)	8 (19)	4 (40)
Adverse events unrelated to trial, n (%)			
Serious	4 (11)	3 (7)	3 (30)
Minor	24 (63)	19 (45)	6 (60)
Type of adverse event (related to trial), n (%)[†]			
Hospital admission	0 (0)	0 (0)	0 (0)
Respiratory illness	0 (0)	0 (0)	0 (0)
Skin reaction to dressing (ActivPAL4)	3 (8)	0 (0)	2 (20)*
Cardiovascular impairment	0 (0)	1 (2)	0 (0)
Musculoskeletal impairment	3 (8)	2 (5)	2 (20)
Fall	0 (0)	0 (0)	0 (0)
Exacerbation of other chronic disease	2 (5)	5 (12)	0 (0)
Acute illness – other than respiratory	0 (0)	0 (0)	0 (0)
Planned surgery or procedure	0 (0)	0 (0)	0 (0)
Other	0 (0)	1 (2)	0 (0)
Type of adverse event (unrelated to trial), n (%)[†]			
Hospital admission	5 (13)	3 (7)	3 (30)
Respiratory illness	23 (61)*	13 (31)	5 (50)
Cardiovascular impairment	2 (5)	5 (12)	0 (0)
Musculoskeletal impairment	5 (13)*	0 (0)	0 (0)
Fall	1 (3)	1 (2)	0 (0)
Exacerbation of other chronic disease	8 (21)*	2 (5)	3 (30)
Acute illness – other than respiratory	7 (18)	3 (7)	2 (20)
Planned surgery or procedure	2 (5)	2 (5)	0 (0)
New diagnosis of other condition	0 (0)	0 (0)	3 (30)*
Other	1 (3)	1 (2)	0 (0)

Statistical significance determined through chi-square test. Results represented as n (%) of participants who reported an adverse event.

*Statistical difference between ITT m-PR and CB-PR groups or between dropout and ITT ($p < 0.05$).

[†]multiple responses possible.

CB-PR: centre-based pulmonary rehabilitation group; ITT: intention-to-treat; m-PR: mobile pulmonary rehabilitation group.

DISCUSSION

This is the first randomised controlled trial to rigorously investigate an mHealth PR program (m-PR) that meets all essential and desirable components of PR [6]. The findings from this study demonstrated that mHealth PR was equivalent to centre-based PR for improvements in exercise capacity and superior for improvements in health status. Equivalence was determined for all secondary outcome measures. Both programs had similarly high levels of adherence and were safe, with no reported serious adverse events related to the clinical trial.

Equivalence in exercise capacity was demonstrated and there were no differences between the proportion of participants who achieved the MCID for 6MWD; however, superiority of the m-PR group could not be excluded. The results from this study support previous randomised controlled trials [16, 17] comparing mHealth PR with structured education programs to centre-based PR, which found non-inferiority of mHealth PR programs for improvements in 6MWD. With the absence of any serious AE, the results from the current study, support the notion that mHealth PR can safely deliver a remote PR program to people with COPD without compromising improvements in exercise capacity.

Participants in the m-PR group showed a significant and superior improvement in health status when compared to those in the CB-PR group, with the odds of achieving the MCID of -2 points being 4.8 times higher in the m-PR group. In addition, almost 70% of m-PR participants achieved the MCID of -2 points for CAT score; higher than rates seen in clinical practice for centre-based PR (56%) [104]. A systematic review with meta-analysis, comparing home-based and centre-based PR programs which included education or self-management programs, also found a significant between-group difference in CAT score favouring home-based PR [180] and suggests that a PR program in the home environment may contribute to greater improvements in health status. Participants in the m-PR group in the current study reported high levels of engagement through the PACES questionnaire. A qualitative analysis [244] of the same participants found that m-PR participants enjoyed the flexibility and convenience of the m-PR program, similar to findings from qualitative research evaluating home-based PR [250]. Enjoyment has been identified as a key mediator for adherence and may explain the greater improvements in health status found in the m-PR group. Adherence in this study was determined by participants

attempting more than 70% of exercise sessions, corresponding with PR adherence measurement guidelines [6], however this method does not allow for interpretation of adherence to exercise dose or to the other interventions delivered through the mHealth PR app (e.g. education, self-management skills, physical activity goal-setting). Further research is warranted to determine which mHealth PR app components people with COPD engage with to better understand the findings from this trial and is addressed by the study in Chapter 3.

Additionally, the odds of participants finding that their program was helpful in improving their understanding and self-management of their COPD were significantly higher in the m-PR group and could also explain the greater improvements in health status. Similar findings of improved self-management skills and knowledge have been found in studies evaluating self-management mHealth apps for people with COPD [251-254], and the addition of mHealth yielded greater improvements in self-management skills when compared to exercise and education alone [252]. One randomised controlled trial [253] also found a statistically significant improvement in CAT score when compared to standard care and suggests that increased self-management skills could subsequently improve health status. Participants using the m-PR™ app in the current study were able to monitor their symptoms, track progress, and watch informational videos repeatedly and on demand. In contrast, those in the CB-PR group received face-to-face education during supervised sessions as needed. The m-PR™ app, and the flexibility that it offered, may have enabled people with COPD to engage more effectively with self-management interventions than when delivered through a centre-based PR program, leading to greater improvements in health status.

In the current study, m-PR was found to be equivalent to CB-PR for improvements in HRQoL and for the proportion of participants achieving the MCID for SGRQ. These findings were comparable to other mHealth PR randomised controlled trials [16, 17] that delivered multi-component mHealth PR programs with structured education programs. However, superiority of m-PR for improvements in SGRQ could not be excluded in the present study, possibly related to the unique delivery of an mHealth PR program that included all essential and desirable components. Future research evaluating the effects of mHealth PR programs on improvements in SGRQ should ensure all essential PR components are met.

Equivalence was determined for changes in dyspnoea severity, as measured by mMRC score; however, superiority of m-PR could not be excluded in the per-protocol analysis. Although within-group improvements in mMRC score in both groups were statistically significant, the change may not have been sufficient to be clinically relevant [248]. These findings align with results from two randomised controlled trials [16, 215] which similarly found small changes in mMRC score following both mHealth PR and centre-based PR. While the mMRC is a validated tool to predict hospitalisation rates [93] and prognosis [93, 94] in people with COPD, its sensitivity to detect meaningful changes in dyspnoea following PR may be limited [95] and could explain the small improvements in dyspnoea observed.

Equivalence between m-PR and CB-PR was also determined for improvements in physical activity levels. Only one other mHealth PR randomised controlled trial [17], which did not include physical activity interventions, has examined changes in daily step count when compared to centre-based PR and reported similar findings. Superiority of the m-PR group for improvements in daily step count could not be excluded, potentially related to the CB-PR group not receiving an activity tracker or another physical activity intervention. However, despite all m-PR participants being provided with an activity monitor, only 26 (69%) chose to receive the physical activity intervention across a mean (SD) duration of 4 (1.8) weeks. Of the 22 participants who received the physical activity intervention and had available ActivPAL4 data for analysis, only 11 (50%) reached the MCID. Results from the current study suggest that a short-term digital PA program has similar challenges to centre-based PR in improving physical activity levels and a longer duration of intervention may be necessary.

There were significantly more participants in the CB-PR group who required an extension to their PR program, with more CB-PR participants missing sessions due to public holiday periods, work or social commitment, and for unspecified reasons. With the exception of one CB-PR participant who withdrew from the trial due to work commitments, the missed sessions did not have an impact on adherence rates as PR programs could be extended by up to four weeks, which was standard clinical practice at the local PR sites. However, the ability for PR services to offer extensions is not universal, and the findings from this study highlight clear barriers for CB-PR program completion that may be overcome by offering mHealth PR services.

Adherence to the exercise sessions were equally as high in both the m-PR and CB-PR groups. Only one other randomised controlled trial [16] has compared adherence between mHealth PR and centre-based PR, and found participants in the mHealth PR group had a lower level of adherence. Adherence to other mHealth PR programs were high (range 80% to 100%) in randomised controlled trials [17, 212, 217] that supported programs with regular motivational telephone calls, similar to the current study. The findings from the satisfaction survey in the current study demonstrated that all m-PR participants found communication with the physiotherapist important, and was identified as a key motivator for adherence in a qualitative analysis [244] of the same m-PR participants. Whether the motivational app features within the m-PR™ app also played a role in high adherence is unclear and is explored further in the study in Chapter 3.

Limitations

There are some limitations to this study. Firstly, recruitment was impacted by PR program closures during the COVID-19 pandemic, resulting in a smaller sample size than expected. In addition, sample size calculations were not adjusted for multiple testing and there was greater missing data for end-intervention 6MWD than for CAT score. Consequently, the study was likely underpowered which may limit the validity of the results. Secondly, to mimic real-world scenarios, only participants who were willing and able to use mHealth were recruited, with most participants rating their technology skills as at least adequate and possibly creating a sample bias of users with moderate to high digital literacy. Participant preference and technology skills are important to consider in clinical practice, although over time this is likely to improve as more frequent smartphone users age and become the primary demographic attending PR. Another limitation was that CB-PR within-group differences did not meet the MCID for 6MWD or CAT score despite high adherence to supervised sessions. Analysis of adherence to the CB-PR group's unsupervised sessions was limited as only six (14%) participants filled out the exercise diary, making it difficult to determine whether adherence was low to completing the diary or to performing the unsupervised exercises, the latter supported by findings from a recent cohort study [255]. The proportion of CB-PR participants reaching the MCID for 6MWD and CAT score were, however, similar to previous published research [203], suggesting that those who do not reach MCID may need a different approach to traditional centre-

based PR. The high adherence rates in the m-PR group suggests that mHealth PR, supported by weekly telephone calls, could potentially be used to optimise adherence to a PR program of three sessions a week and provide additional components such as physical activity and self-management interventions, with the added benefit of a comprehensive, automatic record of adherence. Another limitation was the potential bias introduced by only the m-PR participants receiving a physical activity intervention, and from structured group-based education not being available to some CB-PR participants due to COVID-19 pandemic restrictions and staffing limitations. Consequently, the findings from this study may have been influenced by m-PR participants possibly receiving more intervention. Adherence of CB-PR participants to face-to-face group-based and individualised education was not formally recorded and therefore, this could not be compared with m-PR participant adherence with the education videos which was automatically recorded by the m-PR app.

CONCLUSION

This was the first randomised controlled trial to evaluate an mHealth PR program with all essential and desirable components of PR [6] when compared to centre-based PR. mHealth PR was equivalent to centre-based PR for all outcomes, except health status where it was superior. While the results suggest that mHealth PR was equivalent to CB-PR for all outcomes and superior for health status, the study was underpowered, and the results should be interpreted with some caution. The high level of adherence to the pragmatic study protocol, high participant satisfaction and the absence of serious adverse events, suggest that mHealth PR was safe and achievable for people with COPD. A multi-component mHealth PR program, like the m-PR™ app, is a potential management option for people with COPD with adequate technology skills.

CHAPTER THREE

ENGAGEMENT AND ADHERENCE TO A MOBILE HEALTH PULMONARY REHABILITATION (m-PR) APPLICATION: A SINGLE- ARM ANALYSIS OF A RANDOMISED CONTROLLED TRIAL

The following conference presentations and awards are based on the work in this chapter.

CONFERENCE PRESENTATIONS

Brown, S. (2024, November 29). *Engagement and adherence to the mobile pulmonary rehabilitation (m-PR) app*. [[Poster Presentation](#)]. North Shore and Ryde Health Service Allied Health Symposium, Sydney, Australia.

Brown, S. (2024, March 24). *Engagement and adherence to the mobile pulmonary rehabilitation (m-PR) app*. [[Poster Presentation](#)]. TSANZSRS 2024 The Australia & New Zealand Society of Respiratory Science and The Thoracic Society of Australia and New Zealand (ANZSRS/TSANZ) Annual Scientific Meeting for Leaders in Lung Health & Respiratory Science; May 23–27 2024.

Brown, S. (2023, December 1). *Engagement and adherence to the mobile pulmonary rehabilitation (m-PR) app*. [[Oral Presentation](#)]. North Shore and Ryde Health Service Allied Health Symposium, Sydney, Australia.

AWARDS

Brown, S. (2023). Committee's Choice Award at North Shore and Ryde Health Service Allied Health Symposium, Sydney, Australia; December 1 2023, for oral presentation titled *Engagement and adherence to the mobile pulmonary rehabilitation (m-PR) app*.

BACKGROUND

Pulmonary rehabilitation, traditionally delivered as a supervised, centre-based program, improves exercise capacity and HRQoL in people with COPD [71]. Global issues with poor access, uptake and completion of PR [5] have led recent international clinical practice guidelines to recommend that people with COPD be offered the option of telerehabilitation PR or centre-based PR [4]. However, concerns have been raised [185, 186] regarding participant adherence when PR exercise sessions are unsupervised.

As summarised in Chapter 1, randomised controlled trials [16, 17, 212, 214, 217] have shown that adherence rates to mHealth PR programs vary (40% to 100%), but may be optimised with the support of regular health coaching with a healthcare professional [17, 212, 217]. Program adherence has been measured in several mHealth PR randomised and non-randomised controlled trials [16, 17, 212, 214, 217, 220, 222, 223, 226, 227] with most [16, 212, 214, 220, 222, 223, 226] using exercise sessions attempted as the adherence threshold. Although this method gives some understanding of program adherence, it does not determine whether participants are adherent to the amount of exercise prescribed. Only two studies [17, 227] have examined adherence to the amount of exercises prescribed using duration and frequency, with differing adherence rates found (20% to 82%). Furthermore, mHealth PR programs include different components alongside exercise training (Table 1.2). To fully interpret the effects of mHealth PR on clinical outcomes, it is essential to assess whether people with COPD actively engage with, and adhere to, these different mHealth PR program components.

Engagement, characterised by any interaction with an app, can be tracked through system-recorded data [17, 212, 214-217, 220, 222, 223, 225, 227, 237].

Engagement to mHealth PR apps have been investigated through studies of varying quality and methodologies, largely characterised by lack of randomisation [220, 223], absence of a control group [221, 225] or not fulfilling the essential components of PR [212, 213, 218, 221]. Overall engagement differed between studies, with 61% to 86% [212, 213, 218, 221, 225] of participants accessing the mHealth PR app at least once, and app engagement declining over time in some mHealth PR apps [213, 214, 218] but not others [220]. Similarly, studies [214, 221, 225] have reported conflicting

findings on whether participants engaged more with the exercise [214] or the self-management components [221, 225].

Adherence, characterised by whether a person's engagement behaviour corresponds with the agreed recommendations from a healthcare professional [256], can also be tracked through system-recorded data [17, 212, 214-217, 220, 222, 223, 225, 227, 237]. Program components can be prescribed as tasks for the participants to complete and can include submitting exercise sessions and symptom questionnaires and watching educational videos. Adherence to mHealth PR app tasks, other than the exercise program, have been rarely evaluated. Some studies [214, 223, 225] have found high adherence to education tasks and others [225] low adherence to watching exercise videos, with only one study [214] evaluating adherence over time and reporting high adherence attrition to the education and self-management tasks and low adherence attrition to the exercise tasks. Although these studies have provided some insight into app adherence, this has yet to be rigorously investigated with an mHealth PR app that contains all 13 essential components of PR [6].

Results from the randomised controlled equivalence trial, presented in Chapter 2, demonstrated that people with COPD were equally as adherent to attempting exercise sessions in an mHealth PR and centre-based PR program. Further evaluation of how the participants engaged with, and adhered to, the amount of exercise prescribed, and the other m-PR™ app features would allow for a comprehensive interpretation of the clinical findings reported in Chapter 2. Therefore, the aim of the current study was to use system-recorded data to characterise the engagement behaviour and evaluate the adherence of people with COPD to the multiple components of an mHealth PR app. The work contained in this chapter was part of a broader evaluation, with the qualitative results reported separately in the thesis of another Higher Degree by Research student.

METHODS

Study Design and Participants

This study was a secondary analysis of the single-blinded, multi-centre, equivalence randomised controlled trial presented in Chapter 2. Participants who were randomised to the intervention group (m-PR) were included in this analysis. Those

who withdrew their consent during the intervention period were excluded from the analysis. This study was conducted and reported in accordance with the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines [257].

Procedure

Participants in the randomised controlled trial in Chapter 2 were randomised to either the control (CB-PR) or intervention group (m-PR) in a 1:1 ratio. A full description of the CB-PR and m-PR program can be found in Chapter 2. Participants in the m-PR group had one week to familiarise themselves with the m-PR™ app on a test account (“Week 0”). Participants were then asked to log out of their test account and log in to their individualised program account, where they were given several tasks to complete each week during the eight-week program. m-PR program components are detailed in Appendix 5 and 6. Tasks included viewing an exercise program of three sessions a week (endurance and resistance exercises) and submitting completed exercise data, watching informational videos (educational, exercise and inhaler technique videos), viewing and submitting data for daily health goals (e.g. daily step count) and completing a daily symptom monitoring questionnaire (custom-designed) and weekly questionnaires on health status (CAT) and dyspnoea (mMRC). If prescribed, the participants’ COPD medication action plans [258] would be available within the m-PR™ app for them to view. Participants were also shown and had access to other resources through the ‘menu’ on the m-PR™ app (e.g. stretches, safety guide and tracking of task data over time). However, participants were given no directions on how often to access these resources. Participants were given the option to use an activity tracker (FitBit Inspire, Fitbit Inc, San Francisco, USA) to track their daily step count. Those that chose to have daily step goals were required to view their daily step count on their activity tracker and then manually submit their step count every day, with the option to monitor their recorded step data as a list or as a graph over time. Health coaching was provided to participants through automated in-app notifications and through weekly telephone calls with the physiotherapist. Participant interactions with the app were sent to the m-PR™ app clinician portal that allowed the physiotherapist to track their progress and customise their program in real-time.

Outcome Measures

Baseline characteristics were collected including age, sex, body mass index (BMI), smoking status, employment status, pulmonary function testing, functional exercise capacity (6MWD), health status (CAT), preferred spoken language, and level of technology skills, which have been described in detail in Chapter 2.

System-recorded data, also known as 'click' data, reflected participant interactions with the m-PR™ app. Data were collected from each participant's m-PR™ test account and individualised program account, exported from the m-PR™ clinician portal at the end of the eight-week mHealth PR program to an online spreadsheet (Microsoft® Excel® for Microsoft 365, Microsoft Corporation, Redmond, Washington, US) and then separated into engagement and adherence activity. Engagement was characterised as any interaction with the app whereas adherence compared these interactions with the targets set with the participant at the beginning and throughout their program. Click data were also separated into the designated tasks on the app including the rehabilitation program (exercises [endurance and resistance] and informational videos [educational, exercise and inhaler technique]), daily health goals (e.g. daily step goals), symptom monitoring, in-app notifications, medication action plan and the menu.

Engagement

App engagement was characterised by participants opening the m-PR™ app and interacting with at least one task and was measured as either (i) overall app engagement: the number of participants who engaged with the m-PR™ app at least once over their eight-week program, or (ii) weekly app engagement: the number of days a participant engaged with the m-PR™ app each week. Engagement behaviour for individual tasks within the m-PR™ app was also measured as either (i) overall task engagement: the number of participants who engaged with a certain task at least once over their eight-week program, or (ii) weekly task engagement: the number of participants who engaged with a certain task at least once each week. The click data used to determine participant engagement is summarised in Table 3.1. In addition, the number of videos (educational, exercise and inhaler technique) and questionnaires (daily symptoms, CAT, mMRC) that were accessed were analysed.

Table 3.1. Click data and adherence targets used for m-PR™ app task engagement and adherence levels.

App Task	Engagement Click Data	Adherence Click Data	Adherence Targets
Exercise	Exercise session accessed	Exercise submitted (endurance and resistance)	≥70% of sessions attempted
		Exercise dose submitted (endurance and resistance)	≥70% exercise dose submitted*
Videos	Video accessed (educational, exercise and inhaler)	Video watched until end* (educational, exercise, inhaler)	≥70% of videos watched until end†
Daily Health Goals	Goal submitted	Goal submitted	≥70% of goal sessions attempted
		Goal dose submitted	≥70% of goal dose submitted*
		Goal graph viewed	N/A
Symptom Monitoring	Symptom questionnaire accessed (daily symptom, CAT, mMRC)	Symptom questionnaire completed (daily symptom, CAT, mMRC)	≥70% of symptom questionnaires completed
Notifications	Notification envelope accessed	N/A	N/A
Action Plan‡	Action plan accessed	N/A	N/A
Menu	Menu item accessed	N/A	N/A

*dose adherence only considered if data were submitted for more than 70% of prescribed sessions; †videos considered watched until the end if ≥ 90% of video duration reached; ‡COPD medication action plan [258]; CAT: COPD Assessment Test; mMRC: modified Medical Research Council dyspnoea scale; N/A: Not Applicable.

Adherence

Overall app adherence was determined if a participant successfully activated their individualised m-PR™ program account. Adherence to individual tasks were measured as either (i) overall task adherence: the number of participants who adhered to set targets, or (ii) weekly task adherence: the number of participants who adhered with set targets each week. Click data were used to determine adherence, with adherence targets summarised in Table 1. Exercise and daily health goal adherence were reported as both session adherence (i.e. the proportion of sessions attempted) and dose adherence (i.e. the proportion of sessions completed when considering prescribed dose). Exercise dose variables were duration for endurance exercises and repetitions for resistance exercises. Daily health goal dose varied depending on the type of goal set (e.g. step count for daily step goals). In addition, the number of videos watched (defined as $\geq 90\%$ of video duration reached) and the number of questionnaires completed were analysed.

Statistical Analyses

All statistical analyses were performed using SPSS (Version 22 for Windows, IBM Corporation, Armonk, New York, USA). Continuous variables were reported as mean and SD, mean and range, or as a percentage. Categorical variables were reported as count and percentage.

RESULTS

Participant flow is summarised in Figure 3.1. A total of 44 participants were randomised to the intervention group with baseline characteristics summarised in Table 3.2. Six participants withdrew due to medical reasons unrelated to the clinical trial and the remaining 38 participants were included in the analysis.

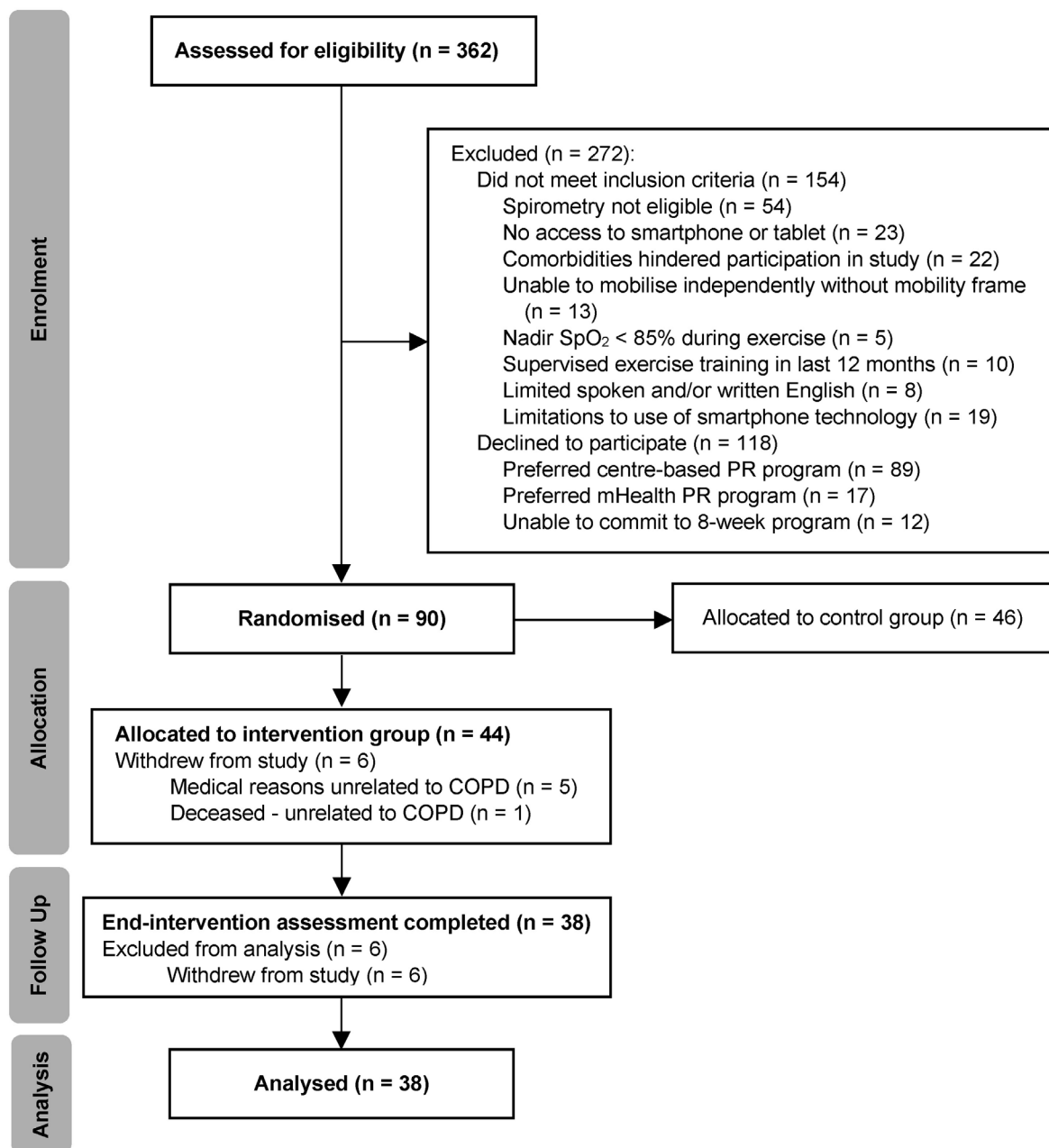


Figure 3.1. Participant flow diagram. Indicated are the study participants included in this single-group analysis of a randomised controlled trial.

Table 3.2. Baseline characteristics of m-PR participants.

Characteristics	Results
Participants, n	44
Age, years	75 (7)
Sex, Female, n (%)	21 (48)
Height, m	1.7 (0.1)
Weight, kg	79 (17)
BMI, kg/m ²	27 (5)
Smoking status, n (%)	
Current Smoker	7 (16)
Ex-smoker	32 (74)
Non-smoker	5 (11)
Smoking history, pack-years*	32 (27)
Employment status, n (%)	
Employed	6 (14)
Not working	38 (86)
Pulmonary function	
FEV ₁ L	1.45 (0.47)
FEV ₁ % predicted	58 (15)
FVC L	2.89 (0.84)
FVC % predicted	86 (19)
FEV ₁ /FVC %	51 (11)
6MWD m	414 (85)
6MWD % predicted	69 (13)
Health Status (CAT)	17 (8)
Preferred language (English), n (%)	42 (95)
Technology skills (Adequate or better) [†] , n (%)	39 (91)

Values are presented as mean (SD) unless otherwise stated. No statistically significant difference between groups for any characteristic. Technology skills were assessed through a custom-designed questionnaire where participants rated their overall technology skills on a 6-point Likert scale from 'Very Poor' to 'Very Good'.

*smoking history available for n = 39; [†]missing technology skills data n = 1; Values are presented as mean (SD) unless otherwise stated. 6MWD: six-minute walk distance; BMI: body mass index; CAT: COPD assessment test; FEV₁: forced expiratory volume in 1 second; FVC: forced vital capacity; kg: kilogram; L: litres; m: metres; n: number of participants.

Engagement

All participants engaged with at least one task on the m-PR™ app during their program. The m-PR™ app was engaged with on a mean (SD) of 4.8 (0.3) days each week with 35 participants (92%) still using the app in the last week of their program (Table 3.3).

Overall engagement levels were high for each of the m-PR™ app tasks and summarised in Table 3.4. Weekly engagement trends are shown in Figure 3.2, with engagement with most tasks declining over time. There was a mean (range) of 15 (15 to 17) educational, 7 (5 to 10) exercise and 2 (0 to 4) inhaler technique videos given to each participant over the eight weeks. Of these, participants started 76%, 86% and 78% of the videos, respectively. Daily and weekly questionnaires were available during all eight weeks of the program with participants commencing a mean (%) 28 (50%) daily symptom, 6 (75%) CAT and 6 (75%) mMRC questionnaires. There was a mean (range) of 38 (26 to 58) notifications sent to each participant.

Adherence

All participants successfully activated their individualised m-PR program account. Overall adherence to each m-PR task varied and is summarised in Table 3.4. Participants were the least adherent to completing the daily symptom questionnaires and the most adherent to attempting the exercise sessions. Weekly adherence trends are shown in Figure 3.2 and show a decline over time with most tasks, with the exception of the step goals and daily symptom questionnaires which both improved slightly over time. On average, participants completed watching 69% of the educational, 51% of the exercise and 74% of the inhaler technique videos and completed 23 (41%) daily symptom, 5 (63%) CAT and 5 (63%) mMRC questionnaires.

Table 3.3. Weekly m-PR™ app activity.

Week of program	Active participants, n	Days with app activity, mean (SD)
0	38	3.8 (2.5)
1	38	4.8 (1.8)
2	37	4.6 (1.9)
3	36	4.7 (1.9)
4	37	5.1 (1.7)
5	37	5.4 (1.8)
6	37	5.0 (2.0)
7	35	4.7 (2.3)
8	35	4.3 (2.4)

App activity was considered if a participant engaged with any task. App: application; m-PR: mobile pulmonary rehabilitation app; n: number of participants; SD: standard deviation.

Table 3.4. Overall participant engagement and adherence levels to m-PR™ tasks.

Task	Engagement, n (%)	Adherence, n (%)
Exercise session		
Overall	38 (100)	33 (87)
Endurance	N/A	32 (84)
Resistance	N/A	33 (87)
Exercise dose		
Overall	N/A	28 (74)
Endurance	N/A	29 (76)
Resistance	N/A	28 (74)
Videos (% of participants)		
Educational	38 (100)	21 (55)
Exercise	38 (100)	12 (32)
Inhaler (n = 36)	32 (89)	22 (61)
Daily Step Goals (n = 26)		
Daily Step Count (Sessions)	26 (100)	13 (50)
Daily Step Count (Dose)	N/A	11 (42)
Step Graph Viewed	20 (77)	N/A
Questionnaires		
Daily Symptom	38 (100)	5 (13)
CAT	38 (100)	20 (53)
mMRC	38 (100)	21 (55)
Notifications	37 (97)	N/A
Action Plan*† (n = 8)	7 (88)	N/A
Menu	37 (97)	N/A

Number of participants was n = 38 unless otherwise stated; *COPD medication action plan [258]; †No participants were prescribed an action plan prior to study commencement; n: number of participants; N/A: not applicable; CAT: COPD Assessment Test; mMRC: modified Medical Research Council dyspnoea scale

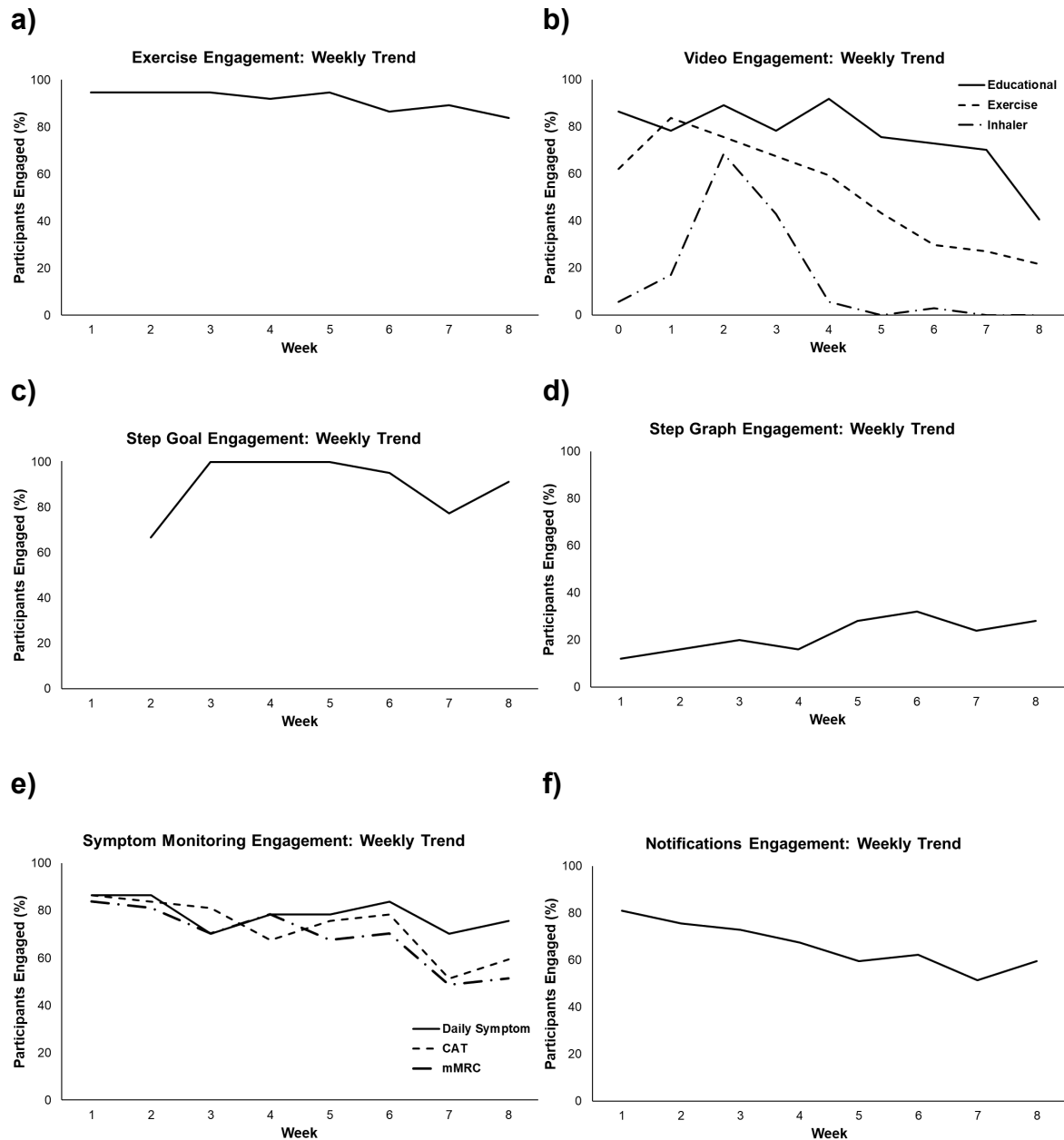


Figure 3.2a-f. Weekly engagement trends to various m-PR™ app tasks.
 a) exercise sessions; b) educational, exercise and inhaler technique videos including test week (week 0); c) step goals (n = 26, no step goals were prescribed in week 1); d) step graph function (n = 26); e) daily symptom questionnaire, CAT and mMRC; f) in-app notifications.
 CAT: COPD assessment test; mMRC: modified Medical Research Council dyspnoea scale.

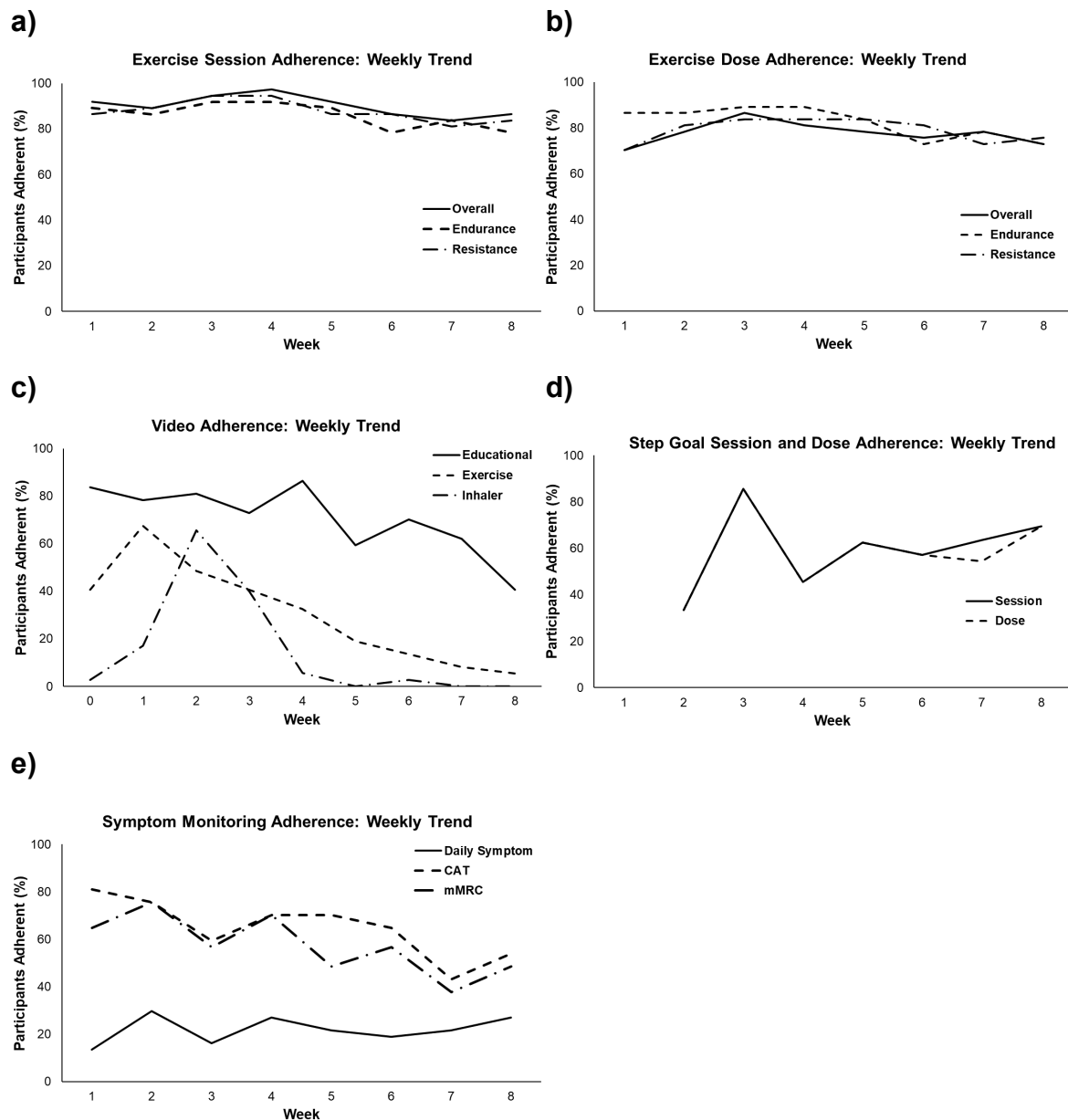


Figure 3.3a-e. Weekly adherence trends to various m-PR™ app tasks.

a) exercise sessions including breakdown into endurance and resistance exercise; b) exercise dose including breakdown into endurance and resistance exercise; c) educational, exercise and inhaler technique videos including test week (week 0); d) step goal session and dose (n = 26, no step goals were prescribed in week 1); e) daily symptom questionnaire, CAT and mMRC.

CAT: COPD assessment test; mMRC: modified Medical Research Council dyspnoea scale.

DISCUSSION

This is the first study to comprehensively examine engagement and adherence to an mHealth PR app where its use in the PR program included all essential and desirable components of PR. Results from this single-arm secondary analysis of the randomised controlled trial presented in Chapter 2 demonstrated that people with COPD had a high level of engagement and adherence, both overall and to individual app tasks. Despite engagement and adherence trends to most tasks other than the exercise program declining over time, general app usage remained consistent across the eight weeks. The results from the current study suggest that people with COPD can engage and adhere highly to multiple components of an mHealth PR app and support the findings from Chapter 2 that mHealth PR can be recommended to people with COPD as an effective option.

Overall app engagement and adherence was excellent, with all participants successfully activating and accessing the m-PR™ app. App activation rates to other mHealth PR apps have been lower (69% to 85%) [213, 218, 220, 221, 225], possibly related to participants not being contacted by healthcare professionals beyond the point of randomisation. Participants in the current study were highly engaged with the m-PR™ app each week, interacting with the app a mean (SD) 4.8 (0.3) days each week and with 92% of participants still accessing the app in the final week. These findings exceed those reported in other mHealth PR studies [213, 214, 218, 220, 223], which did not provide communication with a healthcare professional beyond the point of randomisation nor incorporate motivational app features. Findings from a qualitative analysis [244], which included participants recruited to the current study, identified that the regular contact with the physiotherapist was a strong facilitator to adherence. These collective results suggest that regular contact with a healthcare professional may be crucial for sustaining app engagement over time.

The exercise tasks in the m-PR™ app were the key focus of the program and are an essential component of PR [6]. Engagement and adherence, both overall and weekly, were highest to the exercise tasks. This aligns with findings from a recent mHealth PR randomised controlled trial [214] which reported that although the overall adherence rate was low (40%), more participants were engaged and adherent to the exercises tasks, being the core component of the app, compared to the education and self-management tasks. In contrast, other multi-component

mHealth PR studies [221, 225], which did not specify to participants which app tasks to engage with, found higher engagement with the self-management tasks than the exercise tasks, suggesting that participants may require additional encouragement to complete exercise tasks when programs contain multiple components. Exercise adherence was high in the present study, with 87% of participants being adherent to the exercise sessions. Adherence to exercise dose was lower (74%) than that to exercise session but remained moderately high and consistent across exercise types. These findings were comparable to those of a randomised controlled trial [17] which, similar to the m-PR™ app, evaluated an mHealth PR app incorporating motivational app features and a customisable exercise program, and reported that on average 82% of total exercise duration was completed. In contrast, an mHealth PR app without these features was evaluated through a cohort study [227] and led to only 20% of participants adhering to the prescribed exercise dose despite the mHealth PR program including all essential components of PR. As detailed in the randomised controlled trial in Chapter 2 (Table 2.6), most of the m-PR participants found the exercise sessions, goal setting and in-app notifications important and helpful. A qualitative analysis [244] of the same m-PR participants identified that the ability to adjust sessions led to greater enjoyment, and the m-PR™ app motivational features, such as task list completion, goal setting, progress tracking and in-app notifications, were key motivators. Based on these findings, mHealth PR apps that incorporate motivational app features and a customisable exercise program may enable people with COPD to adhere highly to the prescribed frequency and duration of unsupervised exercise sessions, addressing previous concerns raised [185, 186].

Participants in the current study were equally as adherent to the endurance and resistance exercises, regardless of whether session or dose adherence was considered. In a randomised controlled trial by Benzo and colleagues [212] which aimed to evaluate the effects of an mHealth PR program on dyspnoea in people with COPD who were unable to attend centre-based PR, participants were equally as adherent to the low-intensity balance and flexibility exercises. However, the absence of endurance and resistance exercises makes it challenging to compare findings with those from the current study. A secondary analysis evaluating adherence to a home-based PR program [259] reported higher adherence rates to the resistance exercises (95%) than to the endurance exercises (50%) and could suggest that mHealth PR

apps, and the inherent app features, may effectively improve adherence to endurance exercises than home-based PR alone.

Overall engagement to the informational videos was high and this was consistent across the different types of videos. This finding was comparable to those reported in other mHealth PR trials [213, 220, 225]. Despite most m-PR participants finding the exercise and education videos easy to use, helpful and important (Table 2.6), there was moderate adherence to the educational and inhaler technique videos and low adherence to the exercise videos. In a study by Flynn and colleagues [223], participants were able to choose between centre-based PR or a comprehensive mHealth PR program, which included exercise, self-management and remote monitoring components. Adherence to the education program was higher than adherence rates reported in the current study, with all participants completing at least 80% of education sessions, possibly related to the interactive nature of the education sessions. The exercise and inhaler videos in the present study were informational, and although available each week, were designed to teach the participants how to perform the exercises and correctly administer inhaler medication, and not as videos to watch whilst performing the tasks. As such, the large attrition in exercise and inhaler video engagement may be a result of participants watching and learning the tasks early during the program and no longer needing the videos in the later weeks. Low adherence to the exercise videos may be explained by participants only watching the short segment at the beginning of the exercise video, which explained the exercise, and not the educational and safety information that was repeated at the end of each video. In contrast, lower attrition occurred with the educational videos, which contained unique information in each video and only two to three videos were prescribed to participants each week. Participants from the current study that were included in the qualitative analysis [244] reported perceived benefit from the education and self-management advice delivered through the app and the regular telephone calls; however, the specific advice and format preferred varied between participants. Overall, these findings indicate that future mHealth PR apps should limit repeated information in videos, ensure variety in informational material and consider integrating other motivational app features, such as interactive chats or gamification, to promote greater levels of adherence to an educational program. In addition,

participant preference should be considered when tailoring an education program to optimise engagement and adherence.

Participants were given the option to monitor and develop goals for daily step count. There was a high level of overall engagement with the daily step goals for the 26 participants who chose to participate, and this was consistent across the eight weeks. This was unlike other mHealth studies that have shown a static [260] or decrease [261, 262] in step goal engagement over time. As reported in Chapter 2 (Table 2.5), the odds of perceiving PR as helpful in motivating increased physical activity were 10 times higher in the m-PR group compared to the CB-PR group. The m-PR participants who were interviewed as part of the qualitative analysis [244] found recording activity on the app rewarding, with many participants reporting that they continued to monitor daily step count after program completion. Although most participants viewed the step graph at least once over the eight weeks, weekly engagement to the step graph was low and improved only slightly over the eight weeks and suggests this may not be an effective motivational strategy. Instead, to enhance physical activity motivation, future mHealth PR apps could consider the integration of an activity monitor and physical activity tasks within the app.

Adherence to the step goal sessions was low ($n = 13$, 50%) when compared to mHealth physical activity studies, where daily step count was automatically synchronised from activity monitors to an app [260, 261, 263-265]. Unlike weekly trends seen with other m-PR™ app tasks, adherence to the daily step goals improved over time. As adherence was only considered if daily step count was entered on at least 5 days in a given week, these findings of increased adherence over time may reflect participants remembering to submit their daily step counts every day. This raises the question of whether asking participants to submit tasks daily is too laboursome for participants and whether automated synchronisation of data from an activity monitor might mitigate this issue.

When considering daily and weekly questionnaires, overall engagement was high with each questionnaire. However, adherence to the weekly questionnaires was lower, with 53% of participants being adherent to the CAT questionnaires and 55% to the mMRC. Studies investigating other mHealth PR apps have found varying levels of adherence, with 57% [221] to 100% [225] of participants completing a CAT

questionnaire at least once. The slightly lower adherence that was found in the current study may be due to the higher adherence target that was set, with participants required to complete five or more questionnaires over the eight-week program to be considered adherent. When considering the higher target level, participants from the current study had a higher adherence rate when compared to a similar multi-component mHealth PR app [225]. There was low adherence to the daily symptom questionnaires, with only 13% of participants being considered adherent. Participants in the current study were only considered adherent to the daily symptom questionnaire if it was completed on at least five days in any given week. Coupled with daily questionnaire adherence trends which, similar to the daily step goals, showed a slight improvement over time, these findings suggest that the requirement to submit data daily may be too frequent, and adherence may improve if questionnaires were required less frequently. Engagement and adherence to the weekly questionnaires declined over time and may highlight an element of questionnaire fatigue. However, the findings from Chapter 2 (Table 2.6) demonstrated that most m-PR participants found the symptom monitoring features easy to use, helpful and important and indicate that these features should be included in future mHealth PR apps, but consideration should be given to the number and/or frequency of required questionnaires.

Although participants were not given instructions on how often to interact with the in-app notifications, action plan and menu, overall engagement was high. All participants were instructed to complete a COPD medication action plan with their medical practitioner. However, only 21% of participants were prescribed a medication action plan during their program, lower than the rate ($n = 8$ [73%]) reported by an mHealth PR feasibility pilot study [225] and possibly related to participants not raising this with their medical practitioner, or lack of time during medical appointments to complete an action plan. Notifications were sent multiple times each week as a motivational tool that complemented the weekly telephone calls with the physiotherapist. There was initially a high level of engagement with these notifications, but a moderate level of attrition. Considering there had been a decline in engagement and adherence over time to most m-PRTM tasks, it suggests there may need to be other motivational features (e.g. gamification or loyalty rewards)

[266] integrated into future mHealth PR apps to help maintain a consistent level of engagement and adherence.

Limitations

There are some limitations to this study. Firstly, participants were excluded if they did not own a smartphone or tablet or had limitations to the use of technology, which may have created a selection bias of participants with moderate to high digital literacy. This may impact the generalisability of the results when considering clinical implementation of mHealth PR. Secondly, exercise and daily step goal adherence were self-reported and may have been influenced by participants submitting incorrect data. To mitigate this, system-recorded data were cross-checked with participants during weekly telephone calls and exercise adherence was adjusted accordingly. In addition, minor technological issues experienced, as reported in Chapter 2, may have disrupted participant interactions with the m-PR™ app but were resolved quickly and remotely and likely had a minimal impact on the system-recorded data. Despite these limitations, the main strength of this paper is the rigorous nature of the system-recorded data when using a comprehensive mHealth PR app that allowed for an objective assessment of engagement and adherence and measured quantitatively.

CONCLUSION

This study was the first to rigorously investigate engagement and adherence behaviour to multiple mHealth PR app components, as well as using a novel approach in measuring both exercise session and dose adherence. Results have shown that people with COPD had an excellent level of engagement with all m-PR™ app components, possibly explaining the findings from the study in Chapter 2 that found superiority of the mHealth PR group for improvements in health status when compared to centre-based PR. Participants were highly adherent to the exercise tasks, even when accounting for prescribed exercise dose, and this remained high over the eight-week program. There was a general decline in engagement over time with the informational videos, symptom monitoring questionnaires and in-app notifications, prompting the need for future mHealth PR apps to consider integrating other motivational app features to address the issue of attrition. The findings from

this study suggest that it is feasible for people with COPD to be highly engaged with and adherent to multiple components of an mHealth PR app.

CHAPTER FOUR

MOBILE HEALTH PULMONARY REHABILITATION (m-PR) COMPARED TO CENTRE-BASED PULMONARY REHABILITATION IN PEOPLE WITH COPD: A COMPARISON OF RESOURCE USAGE COSTS AND GREENHOUSE GAS EMISSIONS.

The following abstract submission is based on the work in this chapter.

CONFERENCE PRESENTATIONS

Brown, S. (2025, September 30) *Cost and carbon footprint comparison of mobile pulmonary rehabilitation (m-PR) and centre-based pulmonary rehabilitation.*

[Accepted for Poster Presentation]. The European Respiratory Society International Congress 2025; September 27 – October 1 2025.

Brown, S. (2025, October 23). *Resource use costs and greenhouse gas emissions of mHealth pulmonary rehabilitation (m-PR) and centre-based pulmonary rehabilitation.* [Accepted for Oral Presentation]. The Australian Physiotherapy Association Scientific Conference 2025 (APASC25); October 23-25 2025.

AWARDS

Brown, S. (2025). 'Best Abstracts Linked to Sustainability' The European Respiratory Society International Congress 2025; September 27 – October 1 2025, for abstract titled *Cost and carbon footprint comparison of mobile pulmonary rehabilitation (m-PR) and centre-based pulmonary rehabilitation.*

BACKGROUND

Chronic obstructive pulmonary disease is a preventable and treatable chronic lung disease with a significant economic burden globally [38]. PR is strongly recommended as a cost-effective [4, 125, 130], non-pharmacological treatment for people with COPD that improves HRQoL [71] and reduces rates of COPD-related hospitalisations [64, 72]. PR is traditionally delivered as a supervised, group-based program with a broad spectrum of location settings, resources and session frequency used, largely determined by local program funding [14, 75].

Telerehabilitation PR may be an option to overcome some barriers to access, uptake and completion of centre-based PR [4], however as summarised in Chapter 1, there have been limited economic and environmental evaluations of the different telerehabilitation PR programs.

Centre-based PR is considered cost-effective due to a reduction in healthcare utilisation and an improvement in HRQoL in the year following PR [4, 125, 130]. Economic evaluations have estimated that PR is cost-saving up to \$171 USD [130] per session per participant (\$313 calculated in 2024 AUD after adjusting for currency conversion [135] and inflation [136]) or £1,545 [131] per program per participant (\$3268 calculated in 2024 AUD after adjusting for currency conversion [135] and inflation [136]). The resource usage costs to deliver a videoconferencing PR program [144] were higher than those for centre-based PR, yet despite this, the PR programs were found to be equally as cost-effective [144]. In addition, there is some evidence to indicate that videoconferencing PR may reduce GHG emissions due to a reduction in participant travel [210]. However, the absence of clinically meaningful improvements in exercise capacity and HRQoL following two sessions per week of videoconferencing PR may indicate that greater exercise frequency is needed to achieve clinical efficacy. However, this would consequently increase resource usage costs. Therefore, other telerehabilitation PR models that enable unsupervised exercise sessions may be effective at improving clinical outcomes without increasing resource usage costs, but this has yet to be confirmed in the literature.

Based on the findings from the randomised controlled trial in Chapter 2 and the secondary analysis in Chapter 3, mHealth PR can effectively deliver PR to people with COPD, resulting in high levels of engagement and adherence to multiple components of an mHealth PR app. To provide further rationale as to whether

mHealth PR could be offered as standard practice, it is crucial to consider the economic and environmental impacts of delivering such a program to ensure sustainable and cost-effective outcomes are achieved that benefit public health practice. The aims of the current study were to: 1) determine the costs of resources used for delivering mHealth PR when compared to centre-based PR from a societal perspective; and 2) determine the carbon footprint of delivering a PR program through mHealth when compared to centre-based PR, in people with COPD. Base and scenario analyses were undertaken to determine the resource usage costs and GHG emissions associated with mHealth PR and centre-based PR programs under research conditions and when implemented into local clinical practice, respectively.

METHODS

Study design

This study was a secondary cost- and GHG emissions analysis using data from the prospective, single-blinded, multi-centre, equivalence, randomised controlled trial in Chapter 2. A description of the mHealth PR and centre-based PR programs and the findings from the randomised controlled trial have been presented in Chapter 2. This study was conducted and reported in accordance with the CONSORT guidelines [199].

Participants and intervention

In total, 90 participants with a primary diagnosis of COPD were recruited between April 2022 and April 2024 following a comprehensive centre-based PR assessment at one of five metropolitan, government-funded sites in NSLHD, Sydney, NSW, Australia. After baseline assessment, participants were randomised using a computer-generated random sequence in a 1:1 ratio to either the control group (centre-based PR [CB-PR]) or the intervention group (m-PR). All outcome measures as outlined in Chapter 2 were assessed by a blinded assessor at end-intervention, with the final participant assessed in August 2024 (total study period of 28 months from April 2022 to April 2024).

Intervention group

Participants randomised to the m-PR group had a single home-visit from a senior physiotherapist (NSW Health Level 3 Health Professional) [267] where participants were assisted in downloading the m-PR™ app on their personal smartphone or

tablet device. Following this, they had one-week to practice using the m-PR™ app (Week 0) before undertaking eight weeks of unsupervised, home-based PR supported by the m-PR™ app. All m-PR participants were also provided with an activity tracker (Fitbit Inspire, Fitbit Inc, San Francisco, USA) and had the option to participate in daily step goals and weekly physical activity coaching in addition to the exercise training and education program. Health coaching was provided to all m-PR participants through automated in-app notifications and weekly 15-minute telephone calls with a senior physiotherapist. Participants were able to request assistance with troubleshooting the m-PR™ app and help was provided through additional 10-minute telephone calls as needed. If a participant did not have access to wireless internet at home, a wireless wi-fi adapter (Telstra 4GX USB Modem, Telstra Corp Ltd, Melbourne, Australia) and internet plan was paid for and supplied by the research team. The number of exercise sessions attempted were self-reported by participants through the m-PR™ app and automatically transferred to the m-PR™ app clinician web-portal.

Control group

Participants randomised to the CB-PR group attended two sessions per week of supervised, group-based PR over eight weeks and were asked to complete one, unsupervised, home-based session per week. Participants attended one-hour exercise classes at established PR sites across NSLHD. Each NSLHD PR program was supervised by two senior physiotherapists (NSW Health Level 3 Health Professional) [267] due to the remoteness of some of the PR sites and the fact that the PR service also provided interventions to people with complex conditions such as people with lung cancer, pulmonary hypertension and chronic heart failure, who were not recruited to this study. NSLHD classes could facilitate up to eight participants per session due to COVID-19 restrictions at the time, and exercise sessions were held three times a day, on two days each week at each NSLHD PR site. On days that PR exercise sessions were held, NSLHD physiotherapists took 4 hours to deliver three exercise sessions, record clinical notes and set-up and pack down the centre-based PR gyms for each session. Full-time NSLHD physiotherapists would provide PR programs across two PR sites on separate days (i.e. four different days to deliver two separate PR programs). Different government health programs used the exercise gym on the other days of the week. As these

were existing PR programs, randomised controlled trial participants attended group exercise classes with other people who were not recruited to the study. Only the resource usage costs and GHG emissions associated with delivering the PR program to the randomised controlled trial participants were included. The number of attended exercise sessions was recorded for each participant by the physiotherapists.

Resource usage costs

The costs of resources used for delivering the CB-PR and m-PR interventions were estimated using a societal perspective [121] and included unique costs to the healthcare provider and to the participant. The intervention cost items included for both programs are summarised in Table 4.1. Unit costs, the source of these costs and the formulae used to apply unit costs prospectively to each participant for staffing, travel and use of electricity, the m-PR™ app server, equipment and consumables are outlined in detail in Table 4.2. All costs were valued in 2024 AUD.

Staffing costs were calculated using public health salary pay rates in NSW, Australia [267] and were inclusive of employer costs incurred that were in addition to salary costs (on-costs). Travel distances between PR sites and participants' home addresses, were estimated in kilometres (km) using an online navigation web service (Google Maps™ mapping service, Google LLC, California, USA). A monthly cost was associated with hosting the m-PR™ app on an online app server (Amazon Web Services™, Amazon Web Service Inc., Washington, USA) and was divided between the total number of participants who had accessed the m-PR™ app during the entire study period (28 months). Costs for equipment and consumables that were owned by the healthcare provider were taken from quotes from the equipment provider and an annual equivalent cost was calculated for each equipment and the value adjusted to reflect an eight-week intervention duration. The cost of exercise equipment that were shared with other government health services were adjusted to reflect the proportion of time each piece of equipment was used during PR sessions. Resources used by the healthcare provider were collected by a member of the research team who was not blinded to group allocation.

Table 4.1. Resource usage cost components of m-PR and CB-PR programs.

	CB-PR	m-PR
Healthcare provider	<p>Staffing of senior physiotherapists for administrative duties and providing the CB-PR program</p> <p>Electricity use to power healthcare provider-owned exercise equipment, smartphone and laptop devices</p> <p>Equipment (electronic devices, exercise equipment, other)</p> <p>Consumables</p>	<p>Staffing of a senior physiotherapist for administrative duties, home-visits and providing the m-PR program</p> <p>Car fuel use (between PR sites and participant home for one-off home-visit)</p> <p>Electricity use to power healthcare provider-owned exercise equipment, smartphone and laptop devices</p> <p>Online app server fees</p> <p>Equipment (electronic devices)</p> <p>Consumables</p>
Participant	<p>Car fuel use (between home and PR site for exercise sessions)</p> <p>Public transport, parking or toll road fees (between home and PR site for exercise sessions)</p> <p>Electricity use to power participant-owned exercise equipment or smartphones for PR purposes</p> <p>Use of equipment purchased by the participant for home-based sessions (not including electricity use)</p> <p>Participant and carer time lost from work or leisure activities</p>	<p>Electricity use to power participant-owned exercise equipment or smartphones for PR purpose</p> <p>Use of equipment purchased by the participant for home-based sessions (not including electricity use)</p> <p>Participant and carer time lost from work or leisure activities</p>

Resource usage costs from a societal perspective included unique costs to the healthcare provider and to the participant. m-PR participants were not provided with healthcare provider-owned exercise equipment and were not required to travel to PR sites for exercise sessions, and therefore neither were included in the m-PR cost analysis. CB-PR staff were not required to travel between NSLHD PR sites on exercise sessions days and therefore staff travel was not included in the CB-PR cost analysis.

CB-PR: centre-based pulmonary rehabilitation group; m-PR: mobile pulmonary rehabilitation group; NSLHD: Northern Sydney Local Health District; PR: pulmonary rehabilitation.

Table 4.2. Unit costs and greenhouse gas emission factors for PR intervention components.

Intervention component	Unit Cost, AUD	Source of costs	GHG EF, kgCO ₂ e	Source of GHG EF
Staffing, per hour				
Cost calculation for staffing: <i>time spent on activity (hrs) × hourly wage (\$ per hour)</i>				
GHG emissions not applicable for staffing time				
Physiotherapist, (Level 3, Year 1) hourly wage	65.9	Yearly wage taken from NSW Health Service Health Professionals (State) Award 2023 [267]. Hourly wage calculated by dividing yearly wage by 1976 hours (38 hours of paid work a week for 52 weeks) and adding 20% for on-costs (employer costs incurred that are paid in addition to salary costs)	N/A	N/A
Physiotherapist, (Level 2, Year 1) hourly wage	53.7	Yearly wage taken from NSW Health Service Health Professionals (State) Award 2023 [267]. Hourly wage calculated by dividing yearly wage by 1976 hours (38 hours of paid work a week for 52 weeks) and adding 20% for on-costs (employer costs incurred that are paid in addition to salary costs)	N/A	N/A
Average hourly wage for 2 FTE Senior Physiotherapists	59.8	Average hourly wage when 1 FTE Level 3, Year 1 Physiotherapist and 1 FTE Level 2, Year 1 Physiotherapist are employed. Taken as the average of the hourly wages as reported above	N/A	N/A

Table 4.2 continued.

Travel, per km				
Cost calculation for travel: $travel\ distance\ (km) \times cost\ unit\ (\\$ \text{ per km})$				
GHG emission calculation for travel: $travel\ distance\ (km) \times GHG\ EF\ (kgCO_2e\ \text{per km})$				
Staff travel	0.85	Year 2023-2024 from “Cents per kilometre method” Australian Taxation Office [268].	2.70	Average fleet car used by NSLHD PR service was a 2WD petrol wagon with average fuel consumption of 9.3L/100km. GHG EFs for the use of a gasoline car were taken from the DCCEEW 2024 Australian National Greenhouse Accounts Factors [269].
Participant travel	0.85	Year 2023-2024 from “Cents per kilometre method” Australian Taxation Office [268]. Participants reported any out-of-pocket costs associated with parking, tolls and public transport through a custom-designed resource use questionnaire.	2.57 (car) 0 (train) 0.02 (bus)	<u>Car</u> : Average consumer car used in Australia 2024 was 2WD diesel SUV with average fuel consumption of 7.6L/100km [270]. GHG EFs for the use of a diesel car were taken from the DCCEEW 2024 Australian National Greenhouse Accounts Factors [269]. <u>Train</u> : All Sydney trains are electric and use 100% renewable electricity [271]. <u>Bus</u> : Percentage of diesel buses in Melbourne was similar to Sydney. GHG EF taken from City of Melbourne Transport Strategy Refresh report [272].

Table 4.2 continued.

Electricity, per kWh				
Cost calculation for electricity: $equipment\ energy\ usage\ (kWh) \times time\ using\ equipment\ (hours) \times cost\ unit\ (\$ \text{ per kWh})$				
GHG emission calculation for electricity: $equipment\ energy\ usage\ (kWh) \times time\ using\ equipment\ (hours) \times GHG\ EF\ (kgCO_2e \text{ per kWh})$				
Smartphone	0.389	Cost per kWh of average NSW electricity (standard offer only) sourced from the NSW Energy Social Programs Annual Report 2022-23 [273].	0.7	Scope 2 and 3 GHG EF taken from the DCCEEW 2024 Australian National Greenhouse Accounts Factors [269].
Laptop	0.389	Cost per kWh of average NSW electricity (standard offer only) sourced from the NSW Energy Social Programs Annual Report 2022-23 [273].	0.7	Scope 2 and 3 GHG EF taken from the DCCEEW 2024 Australian National Greenhouse Accounts Factors [269].
Treadmill	0.389	Cost per kWh of average NSW electricity (standard offer only) sourced from the NSW Energy Social Programs Annual Report 2022-23 [273].	0.7	Scope 2 and 3 GHG EF taken from the DCCEEW 2024 Australian National Greenhouse Accounts Factors [269].

Table 4.2 continued.

Equipment, per single item				
Cost calculation for equipment: $\frac{\text{cost from provider (\$)} \times \text{proportion of time used by PR service (\%)} \times \text{weeks of PR completed}}{\text{equipment life span (weeks)}}$				
GHG emission calculation for equipment:				
1) <i>as reported by provider or from a similar product</i>				
2) $\text{Weight of item (kg)} \times \text{GHG EF for main equipment materials (kgCO}_2\text{e per kg)}$				
Smartphone	314.00	From provider.	62	Average kgCO ₂ e for the Apple iPhone™ 15 [274] and Google Pixel™ 8 [275], as reported by the manufacturers.
Laptop	1950.00	From provider.	180	HP EliteBook™ 840 G7 [276], as reported by the manufacturer.
Activity monitor	100.80	From provider.	9	Fitbit Charge™ 6 [277], as reported by the manufacturer.
Stationary bike	4499.00	From provider. If purchased by participant, cost taken from the custom-designed resource use questionnaire.	543.57	A proportion of the kgCO ₂ e reported by the manufacturer of the SportsArt G660™ [278]. Proportion determined by comparing the average weight of NSLHD PR stationary bikes in kg to the weight of the SportsArt G660™.
Treadmill	5700.00	From provider. If purchased by participant, cost taken from the custom-designed resource use questionnaire.	1295.59	A proportion of the kgCO ₂ e reported by the manufacturer of the SportsArt G660™ [278]. Proportion determined by comparing the average weight of NSLHD PR treadmills in kg to the weight of the SportsArt G660™.
Hand weights, 0.5kg	3.00	From provider. If purchased by participant, cost taken from the custom-designed resource use questionnaire.	0.89	PVC and Steel from AusLCI Carbon Emission Factors [279]. Waste from DCCEEW 2024 Australian National Greenhouse Accounts Factors [269].

Table 4.2 continued.

Hand weights, 1.0kg	6.00	From provider. If purchased by participant, cost taken from the custom-designed resource use questionnaire.	1.78	PVC and Steel from AusLCI Carbon Emission Factors [279]. Waste from DCCEEW 2024 Australian National Greenhouse Accounts Factors [269].
Hand weights, 1.5kg	9.00	From provider. If purchased by participant, cost taken from the custom-designed resource use questionnaire.	2.66	PVC and Steel from AusLCI Carbon Emission Factors [279]. Waste from DCCEEW 2024 Australian National Greenhouse Accounts Factors [269].
Hand weights, 2.0kg	12.00	From provider. If purchased by participant, cost taken from the custom-designed resource use questionnaire.	3.55	PVC and Steel from AusLCI Carbon Emission Factors [279]. Waste from DCCEEW 2024 Australian National Greenhouse Accounts Factors [269].
Hand weights, 2.5kg	15.00	From provider. If purchased by participant, cost taken from the custom-designed resource use questionnaire.	4.43	PVC and Steel from AusLCI Carbon Emission Factors [279]. Waste from DCCEEW 2024 Australian National Greenhouse Accounts Factors [269].
Hand weights, 3.0kg	18.00	From provider. If purchased by participant, cost taken from the custom-designed resource use questionnaire.	5.32	PVC and Steel from AusLCI Carbon Emission Factors [279]. Waste from DCCEEW 2024 Australian National Greenhouse Accounts Factors [269].
Hand weights, 3.5kg	21.00	From provider. If purchased by participant, cost taken from the custom-designed resource use questionnaire.	6.20	PVC and Steel from AusLCI Carbon Emission Factors [279]. Waste from DCCEEW 2024 Australian National Greenhouse Accounts Factors [269].
Hand weights, 4.0kg	24.00	From provider. If purchased by participant, cost taken from the custom-designed resource use questionnaire.	7.09	PVC and Steel from AusLCI Carbon Emission Factors [279]. Waste from DCCEEW 2024 Australian National Greenhouse Accounts Factors [269].

Table 4.2 continued.

Hand weights, 5.0kg	30.00	From provider. If purchased by participant, cost taken from the custom-designed resource use questionnaire.	8.86	PVC and Steel from AusLCI Carbon Emission Factors [279]. Waste from DCCEEW 2024 Australian National Greenhouse Accounts Factors [269].
Rehabilitation Step	4257.00	From provider. If purchased by participant, cost taken from the custom-designed resource use questionnaire.	194.01	Steel (low alloyed), steel (powder coating) and PVC from AusLCI Carbon Emission Factors [279]. Waste from DCCEEW 2024 Australian National Greenhouse Accounts Factors [269].
Chair	216.00	From provider	30.6	Chair (High Density Stacker) from MSRDesign Embodied Carbon in Commercial Furniture [280]
Stopwatches	14.50	From provider	0.28	PVC from AusLCI Carbon Emission Factors [279]. Waste from DCCEEW 2024 Australian National Greenhouse Accounts Factors [269].
Counters	3.00	From provider	0.09	PVC and Steel from AusLCI Carbon Emission Factors [279]. Waste from DCCEEW 2024 Australian National Greenhouse Accounts Factors [269].
Portable pulse oximeter	990.00	From provider	1.26	Copper, PVC and synthetic from AusLCI Carbon Emission Factors [279]. Waste from DCCEEW 2024 Australian National Greenhouse Accounts Factors [269].
Sphygmomanometer	190.00	From provider	0.82	Synthetic rubber, Nylon and PVC from AusLCI Carbon Emission Factors [279]. Waste from DCCEEW 2024 Australian National Greenhouse Accounts Factors [269].
Laminated paper Borg and RPE scale (70gsm paper)	0.01	From provider	0.05	Paper from UK Government GHG Conversion Factors for Company Reporting [281]. PET and EVA from AusLCI Carbon Emission Factors [279]. Waste from DCCEEW 2024 Australian National Greenhouse Accounts Factors [269].

Table 4.2 continued.

Consumables, per single item					
Cost calculation for consumables: cost from provider (\$)					
GHG emission calculation for consumables:					
1) as reported by provider or from a similar product, or					
2) Weight of item (kg) × GHG EF for main equipment materials (kgCO _{2e} per kg)					
m-PR™ app paper booklet (150gsm paper)	4.12	From provider	0.12		Paper from UK Government GHG Conversion Factors for Company Reporting [281]. Steel from AusLCI Carbon Emission Factors [279]. Waste from DCCEEW 2024 Australian National Greenhouse Accounts Factors [269].
CB-PR home exercise paper booklet (70gsm paper)	0.24	From provider	0.07		Paper from UK Government GHG Conversion Factors for Company Reporting [281]. Steel from AusLCI Carbon Emission Factors [279]. Waste from DCCEEW 2024 Australian National Greenhouse Accounts Factors [269].
Wifi dongle	110.00	From provider	1.02		ABS and copper from AusLCI Carbon Emission Factors [279]. Waste from DCCEEW 2024 Australian National Greenhouse Accounts Factors [269].
Disinfectant wipes (1 wipe from packet of 80)	0.13	From provider	0.001		Cotton from AusLCI Carbon Emission Factors [279]. Waste from DCCEEW 2024 Australian National Greenhouse Accounts Factors [269].
Alcohol handwash (1mL per pump from 400mL bottle)	0.03	From provider	0.06		PVC from AusLCI Carbon Emission Factors [279]. Waste from DCCEEW 2024 Australian National Greenhouse Accounts Factors [269].

Table 4.2 continued.

App server, total				
Cost calculation for app server: total cost from provider (\$) ÷ number of participants				
GHG emission calculation for app server: total GHG emissions from provider (kgCO₂e) ÷ number of participants				
m-PR™ app server cost	10,235	Total cost to host m-PR™ app on Amazon Web Services™ over 28 months as provided by the company	293	Total GHG emissions from hosting the m-PR™ app on Amazon Web Services™ over 28 months as provided by the company

All costs are presented as AUD 2024. GHG EFs are presented as 2024 equivalents or from the closest year available. Unit costs and GHG EFs used to calculate costs and GHG emissions for staffing, travel, electricity, equipment, consumables and app server use are presented. Unit costs and GHG EFs were applied to each participant by using the formulae listed under each heading.

ABS: acrylonitrile butadiene styrene; App: application; AusLCI: Australian national Life Cycle Inventory database; AUD: Australian Dollars, CB-PR: centre-based pulmonary rehabilitation group; DCCEEW: Department of Climate Change, Energy, the Environment and Water; EF: emission factor; EVA: Ethylene Vinyl Acetate; FTE: full time equivalent; GHG: greenhouse gases; gsm: grams per square metre; kgCO₂e: kilograms of carbon dioxide equivalents; kWh: kilowatt-hour; mL: millilitres; m-PR: mobile pulmonary rehabilitation group; NSLHD: Northern Sydney Local Health District, PET: polyethylene terephthalate; PR: pulmonary rehabilitation; PVC: polyvinyl chloride; RPE: rate of perceived exertion; UK: United Kingdom.

A cost for the purchase of smartphone devices was not included as participants used personal devices that they owned prior to study recruitment. A custom-designed, self-administered, resource use questionnaire was completed by participants at end-intervention with a blinded assessor and was used to prospectively measure costs to the participant associated with transport, equipment and consumables purchased during the intervention period, and time lost from work or leisure activity due to participating in the PR program.

Carbon footprint

The carbon footprint of delivering the CB-PR and m-PR interventions were measured by estimating GHG emissions and expressed as kgCO₂e [50]. Scope 1 (direct GHG emissions from sources owned by the healthcare provider), Scope 2 (GHG emissions associated with electricity purchased by the healthcare provider), and Scope 3 (indirect GHG emissions other than Scope 2) [146, 147] were included and are summarised in Table 4.3. GHG emission factors (EF), the source of these EFs and the formulae used to prospectively apply EFs to each participant for travel and use of electricity, the m-PR™ app server, equipment and consumables, are outlined in detail in Table 4.2. A custom-designed, self-administered, resource use questionnaire was completed by participants at end-intervention with a blinded assessor and was used to prospectively measure participant travel mode and frequency, and equipment purchased by the participant.

Statistical analysis

All trial data were analysed using an ITT analysis and statistical analyses were conducted using SPSS Statistics (V.29.0; IBM Corp, New York, USA). Resource usage costs and GHG emissions data were described as the mean with SD and median with IQR for each participant. Between-group differences in per-participant mean costs and GHG emissions were analysed through the generalised linear model, using the Tweedie (1.5) distribution and log link function to account for the right-skewed nature of cost data, and to derive the mean difference and 95% CI [282].

Base analysis

Resource usage costs and GHG emissions associated with the m-PR and CB-PR programs were analysed in the context of conducting the randomised controlled trial.

Trial data, and therefore the circumstances underlying the delivery of m-PR and CB-PR at the time of the study, were included in this base analysis.

Table 4.3. Carbon footprint components of m-PR and CB-PR programs.

	CB-PR	m-PR
Scope 1	Nil.	Staff travel (PR sites to participant home for one-off home-visit).
Scope 2	Electricity use to power healthcare provider-owned exercise equipment, laptop computers and smartphone devices.	Electricity use to power healthcare provider-owned equipment, laptop computers and smartphone devices.
Scope 3	Participant car and/or public transport travel (home to PR sites for exercise sessions). Electricity use (participant-owned exercise equipment and smartphone device). Cradle-to-gate and grave emissions for all equipment and consumables.	Electricity use (participant-owned exercise equipment and smartphone device). Online app server emissions. Cradle-to-gate and grave emissions for all equipment and consumables.

Scope 1 emissions represent any direct GHG emissions from the delivery of the intervention. Scope 2 emissions are any GHG emissions associated with electricity purchased by NSLHD. Scope 3 emissions include any indirect GHG emissions other than Scope 2 emissions. Carbon footprint was the summation of Scope 1, Scope 2 and Scope 3 GHG emissions. m-PR participants were not provided with healthcare provider-owned exercise equipment and were not required to travel to PR sites for exercise sessions, and therefore neither were included in the m-PR GHG emissions analysis. CB-PR staff were not required to travel between NSLHD PR sites on exercise session days and therefore staff travel was not included in the CB-PR GHG emissions analysis. Cradle-to-gate emissions represented all GHG emissions associated with the mining, production and manufacturing of equipment and consumables up until the factory gate. Grave emissions represented all GHG emissions associated with end-of-life processes.

CB-PR: centre-based pulmonary rehabilitation group; GHG: greenhouse gas; m-PR: mobile pulmonary rehabilitation group; NSLHD: Northern Sydney Local Health District; PR: pulmonary rehabilitation.

Scenario analysis

A scenario analysis was undertaken by altering components of the CB-PR and m-PR programs to estimate the resource usage costs and GHG emissions associated with implementing the programs in real-world conditions within the NSLHD. Comparing the resource usage costs between the base and scenario situations enables conclusions to be drawn around the expected costs and GHG emissions when implemented into clinical practice.

For the CB-PR group, the scenario analysis made the following assumptions: 1) one full-time equivalent (FTE) senior (Level 3) physiotherapist and one FTE junior (Level 2) physiotherapist could supervise the exercise classes, and 2) group-classes could facilitate 10 participants in each class. NSLHD PR classes were supervised by two senior physiotherapists at the time of the randomised controlled trial, related to the disease-background of participants who were not recruited in the study but were present in group-sessions with the CB-PR participants. Some NSLHD PR sites now have a mix of senior and junior physiotherapists and influenced the first assumption. NSLHD PR exercise sessions were also limited at the time of recruitment to 8 participants per class due to COVID-19 restrictions. PR sessions have since returned to the pre-COVID-19 levels of 10 participants per session and is reflected in the second assumption.

For the m-PR group, the scenario analysis made the following assumptions: 1) one FTE senior (Level 3) physiotherapist and one FTE junior (Level 2) physiotherapist delivered the m-PR program, and 2) physiotherapists could manage 68 participants each week who completed nine-week programs (eight weeks of PR and one test-week). The justification for the first assumption is the same as that detailed for the CB-PR group. The estimated m-PR weekly capacity was calculated by comparing the time spent by physiotherapists on CB-PR exercise sessions (i.e. 4 hours) to the time spent by the physiotherapist to provide the m-PR program to participants during the randomised controlled trial (mean 28 minutes per participant per week to provide intervention, manage m-PR™ app administration and record notes, and the time for one-off home-visit that was divided across the nine-week period) (Table 4.4).

The key components that differed between the base and scenario analyses are summarised in Table 4.4. The resource usage costs and GHG emissions derived

from the scenario analysis were presented as mean with SD, median with IQR and between group differences per participant and as an estimate of total resource usage costs and GHG emissions associated with delivering both the m-PR and CB-PR programs over one year with two FTE physiotherapists.

Table 4.4. m-PR and CB-PR program characteristics for base- and scenario-analyses.

	Base analysis – PR characteristics		Scenario Analysis – PR Assumptions	
	m-PR	CB-PR	m-PR	CB-PR
Staffing Levels	1 x Level 3 Physiotherapist.	2 x Level 3 Physiotherapist.	1 x Level 3 Physiotherapist. 1 x Level 2 Physiotherapist.	1 x Level 3 Physiotherapist. 1 x Level 2 Physiotherapist.
PR program participant capacity	38 RCT participants over a 28-month period.	42 RCT participants attended group-based sessions over a 28-month period. 1 x PR site delivered 3 sessions per day, 2 days per week with 8 participants in each session (i.e. 150 participants per year). 2 x FTE physiotherapists able to provide CB-PR program across 2 x PR sites (i.e. 300 participants per year at two PR sites).	2 x FTE physiotherapists able to provide m-PR program to 68 participants a week, (i.e. 377 participants per year if each participant completes a 9-week program [8 weeks of PR and 1 test week]).	1 x PR site able to deliver 3 sessions per day, 2 days per week with 10 participants in each session (i.e. 188 participants per year at one PR site) 2 x FTE physiotherapists able to provide CB-PR program across 2 x PR sites (i.e. 375 participants per year at two PR sites).
Staff time spent on PR intervention, per participant	Home-visit (one-off): 30 minutes + mean travel time of 28 minutes. m-PR™ app initial admin (one-off): 20 minutes. m-PR™ app admin: 5 minutes per week. Weekly telephone call: 15 minutes per week. Troubleshooting phone calls (as needed): 10 minutes.	Initial admin (one-off): 20 minutes. Exercise session: 7.5 minutes (60 minutes / 8 participants). Exercise gym set-up and pack-down for 3 sessions: 2.5 minutes (60 minutes / 24 participants).	Home-visit (one-off): 30 minutes + mean travel time of 28 minutes. m-PR™ app initial set-up (one-off): 20 minutes. m-PR™ app administrative duties: 5 minutes per week. Weekly telephone call: 15 minutes per week. Troubleshooting phone calls (as needed): 10 minutes.	Initial admin (one-off): 20 minutes Exercise session: 6 minutes (60 minutes / 10 participants). Exercise gym set-up and pack-down for 3 sessions: 2 minutes (60 minutes / 30 participants).

Scenario analyses of the CB-PR costs and GHG emissions made the assumptions that: 1) one FTE senior (Level 3) physiotherapist and one FTE junior (Level 2) physiotherapist could supervise the exercise classes, and 2) group-classes could facilitate 10 participants in each class.

Scenario analyses of the m-PR costs and GHG emissions made the assumptions that: 1) one FTE senior (Level 3) physiotherapist and one FTE junior (Level 2) physiotherapist delivered the m-PR program, and 2) two FTE physiotherapists could manage 68 participants each week who completed nine-week programs (eight weeks of PR and one test-week).

CB-PR: centre-based pulmonary rehabilitation group; FTE: full-time equivalent; GHG: greenhouse gas; m-PR: mobile pulmonary rehabilitation group; PR: pulmonary rehabilitation RCT: randomised controlled trial

RESULTS

A total of 90 participants with COPD were randomised with baseline characteristics presented in Table 4.5. There were no differences between groups for any baseline characteristic. Ten participants withdrew from the RCT due to medical illnesses unrelated to the study, with the 80 participants remaining included in the resource usage costs and GHG emissions analysis.

Resource usage costs

Healthcare provider costs for various resources used per participant are summarised in Table 4.6, from the base analysis, and Table 4.7, from the scenario analysis.

Participant costs for various resources used per participant are summarised in Table 4.8. There was no difference in the societal costs per participant between the m-PR (mean [SD] \$572 [71]) and CB-PR (mean [SD] \$552 [164]) programs from the base analysis (MD \$21, 95% CI -\$46 to \$88, $p = 0.143$). The healthcare provider spent a mean \$190 (95% CI, \$140 to \$240, $p < 0.001$) more per participant when delivering the m-PR program during the randomised controlled trial. Participants experienced a mean cost saving of \$168 (95% CI, \$136 to \$201, $p < 0.001$) per participant when completing the m-PR program compared to the CB-PR program.

The scenario analysis found that if implemented in real-world conditions in NSLHD, the m-PR program societal costs (mean [SD] \$298 [65]) would be associated with a mean cost-saving of \$144 (95% CI \$91 to \$197, $p < 0.001$) per participant when compared to the CB-PR program (mean [SD] \$442 [149]). There was no significant difference in healthcare provider costs between the m-PR (mean [SD] \$289 [57]) and CB-PR (mean [SD] \$265 [65]) programs from the scenario analysis (MD \$25, 95% CI -\$8 to \$58, $p = 0.14$). Participant cost-savings were not impacted by the scenario assumptions and therefore were the same as in the base analysis. The societal resource usage costs associated with delivering the m-PR for one year with two FTE physiotherapists was approximately \$58,088 lower when compared to a one-year CB-PR program (Figure 4.1).

Table 4.5. Baseline characteristics

Characteristics	m-PR	CB-PR
Participants, n	44	46
Age, years	75 (7)	75 (6)
Sex, female, n (%)	21 (48)	27 (59)
BMI, kg/m ²	27 (5)	26 (6)
Employment status, n (%)		
Employed	6 (14)	3 (7)
Not working	38 (86)	43 (93)
Pulmonary function		
FEV ₁ L	1.45 (0.47)	1.35 (0.49)
FEV ₁ % predicted	58 (15)	55 (14)
FVC L	2.89 (0.84)	2.71 (1.02)
FVC % predicted	86 (19)	84 (19)
FEV ₁ /FVC %	51 (11)	51 (10)
Severity of COPD, n (%)		
GOLD I	1 (2)	0 (0)
GOLD II	29 (66)	31 (67)
GOLD III	12 (27)	14 (30)
GOLD IV	2 (5)	1 (2)
Comorbidities, n (%) ^δ		
Presence of any comorbidity	44 (100)	46 (100)
Respiratory medications devices ^δ		
Pressurised metered-dose inhaler, n (%)	31 (70)	29 (63)
Dry-powder inhalers, n (%)	27 (61)	30 (65)
Soft mist inhaler, n (%)	9 (20)	18 (39)
Technology skills (adequate or better) ^ε , n (%)	39 (91)	41 (91)
6MWD, metres	414 (85)	431 (91)
CAT, points	17 (8)	17 (6)
Participant one-way travel distance from home to PR site, km	6.3 (5)	6.4 (4)
Proportion of exercise sessions attempted	86 (23)	87 (23)

Values are presented as mean (SD) unless otherwise stated. No statistically significant difference between groups for any characteristic. Technology skills were assessed through a custom-designed questionnaire where participants rated their overall technology skills on a 6-point Likert scale from ‘Very Poor’ to ‘Very Good’.

^αSmoking history available for n = 83 (m-PR = 39 and CB-PR = 44); ^δMultiple responses possible; ^εMissing technology skills data n = 2 (m-PR = 1, CB-PR = 1).

6MWD: six-minute walk distance; BMI: body mass index; CAT: COPD Assessment Test; FEV₁: forced expiratory volume in 1 s; FVC: forced vital capacity; GOLD: Global Initiative for Chronic Obstructive Lung Disease; kg: kilogram; km: kilometre; m-PR: mobile pulmonary rehabilitation group.

Table 4.6. Resource usage costs per participant from the healthcare provider perspective (base analysis).

	Cost (AUD)				Between-group mean difference	p-value
	CB-PR (n = 42)		m-PR (n = 38)			
	Mean (SD)	Median (IQR)	Mean (SD)	Median (IQR)	MD (95% CI)	
Staffing	346 (87)	381 (0)	278 (53)	287 (39)	-68 (-106 to -30)	<.001*
Program (wages)	346 (87)	381 (0)	203 (44)	214 (14)		
Home-visit (wages and travel)	N/A	N/A	75 (25)	68 (32)		
Electricity	5 (2)	6 (0.1)	0.1 (0.01)	0.1 (0)	-5 (-6 to -5)	<.001*
Electronic Devices	0.04 (0.01)	0.04 (0)	0.1 (0.01)	0.1 (0)		
Exercise Equipment	5 (2)	6 (0.1)	N/A	N/A		
m-PR app server	N/A	N/A	244 (0)	244 (0)		
Equipment	21 (6)	23 (1)	27 (11)	27 (3)	6 (2 to 10)	0.005*
Exercise equipment	11 (4)	12 (1)	N/A	N/A		
Electronic Devices	7 (2)	8 (0)	27 (11)	27 (3)		
Other	3 (1)	3 (0)	N/A	N/A		
Consumables	3 (1)	3 (0)	4 (0)	4 (0)	2 (1 to 2)	<.001*
Total	375 (94)	412 (6)	564 (63)	567 (43)	190 (140 to 240)	<.001*

All costs are presented in 2024 Australian Dollars (AUD). Between-group mean differences analysed using the generalised linear model and presented as m-PR mean data minus CB-PR mean data. Base analysis represented costs associated with the delivering the PR programs in a randomised controlled trial. Electronic devices included smartphone devices, laptop computers, wi-fi dongle device (m-PR group only) and activity monitor (m-PR group only). The total m-PR app server cost (hosted by Amazon Web Services™) for the 28-month study period was divided between the 38 m-PR participants for the base analysis. Exercise equipment used by CB-PR participants included treadmills, stationary bikes, hand weights (0.5kg – 5kg), chairs, exercise steps, counters and/or stopwatches. No exercise equipment was provided by the health care provider to the m-PR participants. 'Other' equipment used by the CB-PR participants only included portable pulse oximeters and portable sphygmomanometers. Consumables refer to single-use items.

*statistically significant (p < 0.05)

AUD: Australian dollars; CB-PR: centre-based pulmonary rehabilitation group; CI: confidence interval; IQR: interquartile range; MD: mean difference; m-PR: mobile pulmonary rehabilitation group; N/A: not applicable; SD: standard deviation.

Table 4.7. Resource usage costs per participant from the healthcare provider perspective (scenario analysis).

	Cost (AUD)				Between-group mean difference	p-value
	CB-PR (n = 375)		m-PR (n = 377)			
	Mean (SD)	Median (IQR)	Mean (SD)	Median (IQR)	MD (95% CI)	
Staffing	245 (60)	269 (0)	257 (50)	264 (42)	12 (-18 to 42)	0.43
Program (wages)	245 (60)	269 (0)	187 (41)	194 (22)		
Home-visit (wages and travel)	N/A	N/A	69 (23)	63 (30)		
Electricity	5 (2)	6 (0.1)	0.1 (0.01)	0.1 (0)	-5 (-6 to -5)	<.001*
Electronic Devices	0.03 (0.01)	0.03 (0)	0.1 (0.01)	0.1 (0)		
Exercise Equipment	5 (2)	6 (0.1)	N/A	N/A		
m-PR app server	N/A	N/A	12 (0)	12 (0)		
Equipment	12 (3)	14 (1)	6 (8)	5 (1)	-7 (-9 to -4)	<.001*
Exercise equipment	8 (2)	9 (1)	N/A	N/A		
Electronic Devices	3 (1)	3 (0)	6 (8)	5 (1)		
Other	1 (0.3)	1 (0)	N/A	N/A		
Consumables	3 (1)	3 (0)	4 (0)	4 (0)	2 (1 to 2)	<.001*
Total	265 (65)	291 (5)	289 (57)	294 (45)	25 (-8 to 58)	0.14

All costs are presented in 2024 Australian Dollars (AUD). Between-group mean differences analysed using the generalised linear model and presented as m-PR mean data minus CB-PR mean data. Scenario analysis represented costs associated with PR programs if implemented into clinical practice. Electronic devices included smartphone devices, laptop computers, wi-fi dongle device (m-PR group only) and activity monitor (m-PR group only). The total m-PR™ app server cost (hosted by Amazon Web Services™) for the 28-month study period was divided between 874 participants (based on an estimated 68 participants per week, completing 9-week programs over 28 months) for the scenario analysis. Exercise equipment used by CB-PR participants included treadmills, stationary bikes, hand weights (0.5kg – 5kg), chairs, exercise steps, counters and/or stopwatches. No exercise equipment was provided by the healthcare provider to the m-PR participants. ‘Other’ equipment used by the CB-PR participants only included portable pulse oximeters and portable sphygmomanometers. Consumables refer to single-use items.

*statistically significant (p<0.05)

AUD: Australian dollars; CB-PR: centre-based pulmonary rehabilitation group; CI: confidence interval; IQR: interquartile range; MD: mean difference; m-PR: mobile pulmonary rehabilitation group; N/A: not applicable; SD: standard deviation.

Table 4.8. Cost per participant from the participant perspective.

	Cost (AUD)				Between-group mean difference	p-value
	CB-PR (n = 42)		m-PR (n = 38)			
	Mean (SD)	Median (IQR)	Mean (SD)	Median (IQR)	MD (95% CI)	
Participant travel	145 (93)	128 (139)	N/A	N/A		
Fuel	129 (97)	119 (147)				
Parking	9 (30)	0 (0)				
Public transport	7 (15)	0 (0)				
Electricity	0 (0)	0 (0)	2 (3)	0.02 (1)	2 (1 to 2)	0.002*
Purchased Equipment	1 (3)	0 (0)	1 (4)	0 (0)	0.4 (-1 to 2)	0.67
Time lost from work or other activities	31 (99)	0 (0)	6 (29)	0 (0)	-25 (-58 to 7)	0.12
Patient	30 (100)	0 (0)	5 (29)	0 (0)		
Carer	2 (14)	0 (0)	1 (4)	0 (0)		
Total	177 (132)	158 (162)	9 (30)	0 (8)	-168 (-201 to -136)	<.001*

All costs are presented in 2024 Australian Dollars (AUD). Between-group mean differences analysed using the generalised linear model and presented as m-PR mean data minus CB-PR mean data. The scenario analysis did not impact participant reported costs and therefore is not reported in this table. Participant travel to and from PR sites for the purpose of completing face-to-face exercise sessions were included and therefore was not applicable to participants in the m-PR group. Equipment purchased during the intervention period by the participant for the purpose of completing home-based exercise sessions were included in the analysis. Electricity costs included costs associated with powering electronic devices and exercise equipment for the purpose of completing home-based exercise sessions.

*statistically significant (p<0.05)

AUD: Australian dollars; CB-PR: centre-based pulmonary rehabilitation group; CI: confidence interval; IQR: interquartile range; MD: mean difference; m-PR: mobile pulmonary rehabilitation group; N/A: not applicable; SD: standard deviation.

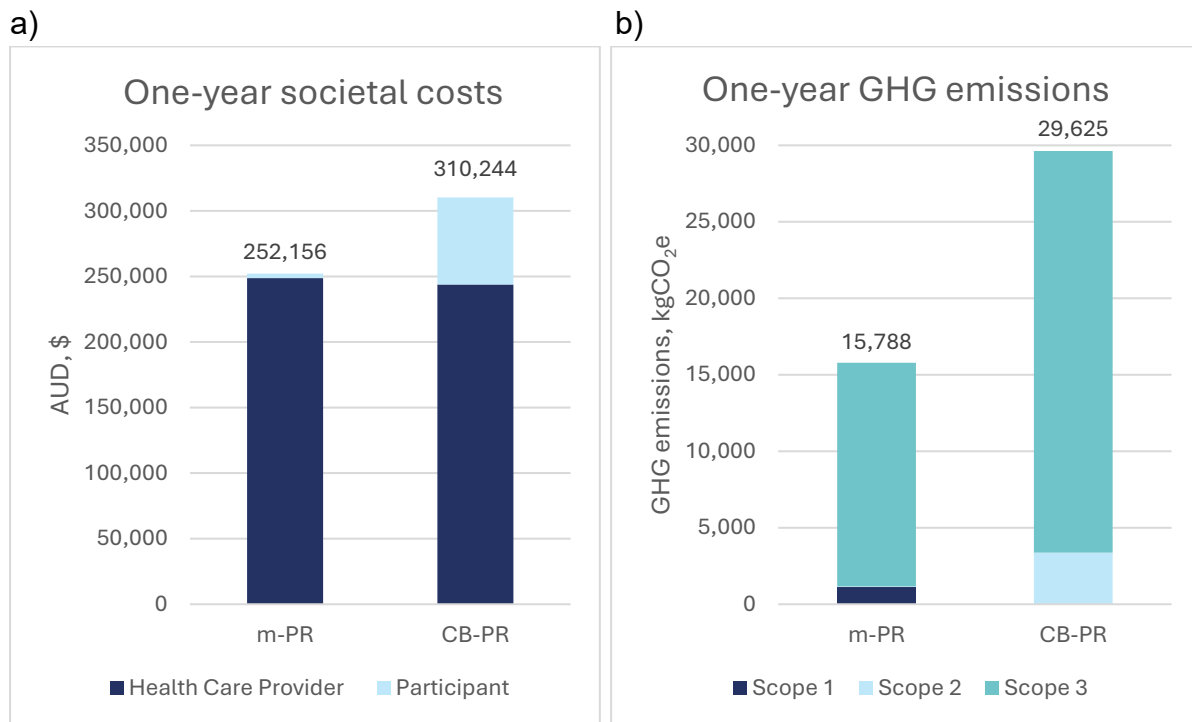


Figure 4.1a-b. One-year resource usage costs and GHG emissions.

The a) resource usage costs and b) GHG emissions associated with delivering the m-PR and CB-PR programs outside of research conditions. Resource usage costs and GHG emissions from the scenario analysis were used to determine these costs over a one-year timeframe where both programs employed 1 FTE Level 3, Year 1 Physiotherapist and 1 FTE Level 2, Year 1 Physiotherapist and were able to provide the CB-PR programs to 375 participants or the m-PR program to 377 participants. AUD: Australian dollars; CB-PR: centre-based pulmonary rehabilitation group; FTE: full-time equivalent; GHG: greenhouse gas; kgCO₂e: kilograms of carbon dioxide equivalent; m-PR: mobile pulmonary rehabilitation group.

Carbon footprint

The Scope 1, Scope 2 and Scope 3 per participant GHG emissions are summarised in Table 4.9, from the base analysis, and Table 4.10, from the scenario analysis.

There was no statistically significant difference in the total GHG emissions between the m-PR and CB-PR programs when performing the base analysis (MD -21kgCO₂e, 95% CI -51 kgCO₂e to 8 kgCO₂e, p = 0.16).

From the scenario analysis, there was a mean reduction of 36 kgCO₂e (95% CI 8 kgCO₂e to 63 kgCO₂e, p < 0.01) per participant when delivering the m-PR program compared to the CB-PR program. The total carbon footprint of delivering the m-PR program for one year was approximately 13,838 kgCO₂e lower than the carbon footprint of a one-year CB-PR program (Figure 4.1).

Table 4.9. GHG emissions per participant (base analysis).

	GHG emissions (kgCO ₂ e)				Between-group mean difference	p-value
	CB-PR (n = 42)		m-PR (n = 38)			
	Mean (SD)	Median (IQR)	Mean (SD)	Median (IQR)	MD (95% CI)	
Scope 1 – Staff travel	N/A	N/A	3 (3)	3 (2)		
Scope 2 - Electricity	9 (3)	10 (1)	0.1 (0.03)	0.1 (0.01)	-9 (-10 to -8)	<.001*
Electronic Devices	0.02 (0.004)	0.02 (0)	0.1 (0.03)	0.1 (0.01)		
Exercise Equipment	9 (3)	10 (1)	N/A	N/A		
Scope 3 – Indirect	71 (121)	45 (51)	55 (210)	17 (8)	-16 (-44 to 12)	0.26
Participant travel	39 (29)	36 (47)	N/A	N/A		
<i>Car</i>	39 (29)	36 (44)				
<i>Public transport</i>	0.5 (2)	0 (0)				
Participant electricity	0 (0)	0 (0)	3 (6)	0.03 (1)		
Consumables	2 (0.5)	2 (0)	0.1 (0)	0.1 (0)		
Equipment	29 (117)	3 (1)	44 (210)	9 (0.1)		
<i>Participant bought</i>	27 (117)	0 (1)	36 (213)	0 (0)		
<i>PR exercise equipment</i>	2 (0.3)	2 (0)	N/A	N/A		
<i>PR electronic devices</i>	1 (0)	1 (0)	9 (0.1)	9 (0)		
<i>PR other equipment</i>	0.01 (0)	0.01 (0)	N/A	N/A		
App server	N/A	N/A	8 (0)	8 (0)		
Total	80 (122)	56 (55)	58 (211)	21 (9)	-21 (-51 to 8)	0.16

Between-group mean differences analysed using the generalised linear model and presented as m-PR mean data minus CB-PR mean data. Base analysis represents costs associated with delivering the PR programs in a randomised controlled trial. Electronic devices included smartphone devices, laptop computers, wi-fi dongle device (m-PR group only) and activity monitor (m-PR group only). The total m-PR™ app server GHG emissions (hosted by Amazon Web Services™) for the 28-month study period was divided between the 38 m-PR participants for the base analysis. Exercise equipment used by CB-PR participants included treadmills, stationary bike, hand weights (0.5kg – 5kg), chairs, exercise steps, counters and/or stopwatches. No exercise equipment was provided by the healthcare provider to the m-PR participants. Other equipment used by the CB-PR participants only included portable pulse oximeters and a portable sphygmomanometer. Consumables refer to single-use items.

*statistically significant (p<0.05)

CB-PR: centre-based pulmonary rehabilitation group; CI: confidence interval; IQR: interquartile range; kgCO₂e: kilograms of carbon dioxide equivalent; MD: mean difference; m-PR: mobile pulmonary rehabilitation group; PR: pulmonary rehabilitation; SD: standard deviation.

Table 4.10. GHG emissions per participant (scenario analysis).

	GHG emissions (kgCO ₂ e)				Between-group mean difference MD (95% CI)	p-value
	CB-PR (n = 375)		m-PR (n = 377)			
	Mean (SD)	Median (IQR)	Mean (SD)	Median (IQR)		
Scope 1 – Staff travel	N/A	N/A	3 (3)	3 (2)		
Scope 2 - Electricity	9 (3)	10 (1)	0.1 (0.03)	0.1 (0.01)	-9 (-10 to -8)	<.001*
Electronic Devices	0.02 (0.004)	0.02 (0)	0.1 (0.03)	0.1 (0.01)		
Exercise Equipment	9 (3)	10 (1)	N/A	N/A		
Scope 3 – Indirect	70 (121)	45 (51)	39 (210)	1 (8)	-30 (-57 to -4)	0.02*
Participant travel	39 (29)	36 (47)	N/A	N/A		
<i>Car</i>	39 (29)	36 (44)				
<i>Public transport</i>	0.5 (2)	0 (0)				
Participant electricity	0 (0)	0 (0)	3 (6)	0.03 (1)		
Consumables	2 (0.5)	2 (0)	0.1 (0)	0.1 (0)		
Equipment	28 (117)	2 (1)	36 (210)	1 (0.1)		
<i>Participant bought</i>	27 (117)	0 (1)	36 (213)	0 (0)		
<i>PR exercise equipment</i>	1 (0.1)	1 (0)	N/A	N/A		
<i>PR electronic devices</i>	0.4 (0)	0.4 (0)	1 (0.03)	1 (0)		
<i>PR other equipment</i>	0 (0)	0 (0)	N/A	N/A		
App server	N/A	N/A	1 (0)	1 (0)		
Total	79 (122)	55 (55)	43 (211)	6 (9)	-36 (-63 to -8)	0.01*

Between-group mean differences analysed using the generalised linear model and presented as m-PR group mean data minus CB-PR mean data. Scenario analysis represents costs associated with PR programs if implemented into clinical practice. Electronic devices included smartphone devices, laptop computers, wi-fi dongle device (m-PR group only) and activity monitor (m-PR group only). Exercise equipment used by CB-PR participants included treadmills, stationary bike, hand weights (0.5kg – 5kg), chairs, exercise steps, counters and/or stopwatches. No exercise equipment was provided by the healthcare provider to the m-PR participants. Other equipment used by the CB-PR participants only included portable pulse oximeters and a portable sphygmomanometer. Consumables refer to single-use items. *statistically significant (p<0.05)

CB-PR: centre-based pulmonary rehabilitation group; CI: confidence interval; IQR: interquartile range; kgCO₂e: kilograms of carbon dioxide equivalent; MD: mean difference; m-PR: mobile pulmonary rehabilitation group; PR: pulmonary rehabilitation; SD: standard deviation.

DISCUSSION

This study was the first to compare the resource usage costs and the carbon footprints of an mHealth PR and centre-based PR program in people with COPD. There were no significant differences between the m-PR and CB-PR programs in terms of societal costs (MD \$48, 95% CI -\$16 to \$113, $p = 0.143$) and GHG emissions (MD -21kgCO_{2e}, 95% CI -51 kgCO_{2e} to 8 kgCO_{2e}, $p = 0.16$) per participant when delivered as part of a randomised controlled trial. If implemented into clinical practice within NSLHD, the scenario analysis demonstrated an expected total resource usage cost-saving of \$137 (95% CI \$86 to \$189, $p < 0.001$) and a reduction in GHG emissions of 36 kgCO_{2e} (95% CI 8 kgCO_{2e} to 63 kgCO_{2e}, $p < 0.01$) per participant when delivering the m-PR program compared to the centre-based PR program. Over the course of one year with two FTE physiotherapists, this would equate to a cost-saving of \$58,088 and a reduction in GHG emissions of 13,838 kgCO_{2e}.

The societal resource usage costs of delivering the m-PR and CB-PR program to the randomised controlled trial participants were \$560 and \$510 per participant, respectively. This was comparably lower than cost-saving thresholds reported for PR programs in the UK (£1,545 per participant per program; \$3159 calculated in 2024 AUD when adjusting for currency conversion [135] and inflation [136]) and in the US (\$171 USD per participant per session; \$313 calculated in 2024 AUD when adjusting for currency conversion [135] and inflation [136]) and although there are limitations with generalising these thresholds to an Australian setting, they could suggest that the m-PR and CB-PR programs were cost-saving. A recent study by Burge and colleagues [144] compared videoconferencing PR to centre-based PR in an Australian setting and found that the costs to deliver the programs were higher than those found in the present study at \$2155 AUD (\$2574 calculated in 2024 AUD after adjusting for inflation [136]) for videoconferencing PR and \$1826 AUD (\$2181 calculated in 2024 AUD after adjusting for inflation [136]) for centre-based PR per participant. Staffing costs to supervise the centre-based PR exercise sessions were similar to those for the CB-PR program in the present study. Instead, the costs were likely higher in the study by Burge and colleagues [144] due to the inclusion of resource usage costs associated with baseline and end-intervention assessments, additional clinical and education time provided and the videoconferencing exercise

sessions which were supervised in small online groups and required expensive telecommunication equipment. In the current study, the resource usage costs of the randomised controlled trial initial and end-intervention assessments were not included as these items constituted research activity rather than intervention and as such was not included in the cost analysis.

Additional staff time for education was not required in the present study as m-PR participants received education through m-PR™ app videos or during scheduled weekly telephone calls, and CB-PR participants received education during session times. The m-PR participants also completed all exercise sessions unsupervised with minimal equipment and required only a 15-minute phone call once per week, far less resource-intensive than the videoconferencing equipment used and the supervision provided for exercise sessions, in the study by Burge and colleagues [144]. Another randomised controlled trial by the same authors [143] compared home-based PR to centre-based PR, where participants in the home-based PR group received 30-minute telephone calls each week and, similar to the m-PR program, required minimal resources. The study estimated that the home-based PR and centre-based PR programs cost the healthcare provider \$327 AUD (\$408 calculated in 2024 AUD after adjusting for inflation [136]) and \$345 AUD (\$430 calculated in 2024 AUD after adjusting for inflation [136]) per participant, respectively. These costs were higher than those found from the scenario analysis in the present study (mean [SD], m-PR: \$289 [57]; vs CB-PR: \$265 [65]). In both the present study and in studies by Burge and colleagues [143, 144], staffing costs were responsible for most of the healthcare provider resource usage costs. Time spent on weekly telephone calls and home-visit sessions were shorter in the m-PR program than those provided in the home-based PR study by Burge and colleagues [143] and could explain why the m-PR healthcare provider resource usage costs were lower. The use of mHealth PR could be employed to reduce required staffing time and ultimately optimise healthcare provider spending; a notion supported in a recent guidance report conducted in the UK [283].

The societal resource usage costs saved when delivering the m-PR program in real-world conditions, as discovered through the scenario analysis, was driven by a reduction in participant costs (MD -\$168, 95% CI -\$201 to -\$136, $p < 0.001$), largely related to eliminating the need for m-PR participants to travel to and from PR sites.

Participants were recruited from metropolitan PR sites only in Sydney, Australia, with an average one-way travel distance of 6.4 km. In contrast, participants in the videoconferencing PR randomised controlled trial by Burge and colleagues [144] were recruited from metropolitan and rural PR sites and consequently had greater distances to travel [210] to access PR sites. Consequently, the participants experienced a larger resource usage cost-saving of approximately \$700 AUD (\$900 in 2024 AUD after taking into consideration inflation [136]) per participant when compared to the findings from the current study. People in regional, rural and remote areas of Australia need to travel greater distances to access health care [166, 167] and the participant resource usage cost savings from accessing mHealth PR instead of centre-based PR would likely be magnified in these areas.

Most of the participants in the present study were not working (n = 81, 90%) and the costs per participant associated with time lost from work or other activities were subsequently low in the m-PR (mean [SD], \$6 [29]) and CB-PR groups (mean [SD], \$31 [99]). People with COPD who are still working and need to take time off from paid work to attend centre-based PR classes could potentially experience a greater resource usage cost-saving if offered mHealth PR. There are challenges with participant uptake, access and completion of centre-based PR programs globally [5] and minimising the costs incurred by participants by offering mHealth PR may be one strategy to overcome some barriers to PR, particularly for those experiencing financial hardship [284].

Staffing costs to provide the weekly intervention were significantly lower in the m-PR group when compared to CB-PR. This was despite the m-PR participants completing the extra 'test week' before starting their PR program. However, overall healthcare provider costs from the scenario analysis were no different between the m-PR and CB-PR programs (MD \$25, 95% CI -\$8 to \$58, p = 0.14) due to the additional costs for the one-off home-visit in the m-PR program. Home-visit costs (mean [SD], \$75 [25]) were lower than those reported for videoconferencing PR [144] and home-based PR [143] programs (\$79 to \$463 AUD; \$94 to \$533 calculated in 2024 AUD when adjusting for inflation [136]), possibly due to greater travel distances and more time required from staff. Decision makers may wish to consider the need and purpose for home-visits to ensure efficient use of healthcare resources.

Resource usage costs associated with the online app server (mean, \$244 per participant) significantly contributed to the overall healthcare provider costs. As found from the scenario analysis, this cost was lower at \$12 per participant when the online app server costs were shared across more participants in a fully operational mHealth PR program. Commercial mHealth PR apps are available in some countries where healthcare providers pay for a license fee instead of app server costs; with fees varying depending on the mHealth PR app and number of annual users [221, 233, 283]. Availability of local mHealth PR apps, associated licensing fees, and projected number of active users will need to be considered by decision makers when implementing mHealth PR.

The delivery of the m-PR program in the present study significantly reduced GHG emissions when compared to CB-PR. Scope 3 emission savings were greatest, primarily due to m-PR participants not travelling to and from PR sites for exercise sessions. Participants were recruited in metropolitan areas with public transport available at all five NSLHD PR sites. Despite this, most of the CB-PR participants travelled by car. Car travel is the most common mode of transport amongst older Australians, with difficulty walking and climbing steps being a major limiting factor to public transport use [285]. Decreased exercise capacity and muscle weakness are commonly found in people with COPD [20, 21, 286], suggesting that improving public transport access to PR sites may not effectively reduce car travel. Targeting digitally supported, home-based PR models that eliminate the need for participant travel has recently been identified as a strategy to reduce GHG emissions [210], with the results from the current study confirming that mHealth PR may be a more environmentally friendly alternative to centre-based PR.

mHealth PR may be an effective strategy to help health jurisdictions reach their net zero targets. Health jurisdictions across Australia have developed planetary health frameworks [287-292] to outline local strategies to reduce healthcare GHG emissions. Implementing mHealth PR across two NSLHD PR sites would reduce GHG emissions of 13,838 kgCO₂e over one year. This is equivalent to 18,000 chest x-rays [293], 170,000 haematology pathology tests [294] or 62 car journeys between Sydney and Melbourne, Australia. Decision makers will be able to use the findings from the scenario analysis to estimate GHG emission savings when implementing mHealth PR programs locally.

Limitations

There were some limitations to this study. Only participants who were willing and able to use mobile technologies were recruited, with most participants rating at least an adequate level of technology skills. As a consequence, there may be a sample bias of participants with moderate to high digital literacy. Another limitation was that participants were recruited at metropolitan PR sites only, and results may underrepresent the potential GHG emission- and resource usage cost-savings for PR programs being offered in regional, rural and remote areas. Resource use and transport mode data from participants were based off self-reported estimates and may be impacted by recall bias; however, this is likely minimal given the short eight-week recall timeframe. Attendance at CB-PR exercise sessions was recorded for study participants only and not for people who were also present for the exercise sessions who were not recruited to the randomised controlled trial. Physiotherapists' time during exercise sessions were divided across eight participants as this was the CB-PR exercise sessions capacity during the trial. This method took a conservative approach and represented a 100% attendance rate, and although CB-PR participant adherence rates were high, this does not represent attendance found in clinical practice [163, 295] and may impact the generalisability of the results. Decision makers should consider local PR attendance rates when interpreting these results.

The resource usage costs and GHG emissions associated with baseline and end-intervention assessments were not included as these were considered research activities only, and so the current study results likely underestimate total costs and GHG emissions for programs that deliver face-to-face assessments. Although an initial centre-based assessment is considered an essential component of PR [6], recent studies [296, 297] have evaluated exercise tests that can be delivered remotely and have found these tests safe and reliable, questioning whether centre-based PR assessments are essential.

Another limitation is that resource usage costs and GHG emissions related to PR site maintenance, cleaning services and lighting were not included in the analysis as all five PR gym spaces were government owned and shared amongst other public services. Consequently, this may have led to an underestimation of costs and emissions associated with the centre-based PR program. Similarly, costs and GHG emissions associated with exercise clothes purchased by the participant were not

evaluated and may underestimate the total cost and carbon footprint of both the mHealth PR and centre-based PR programs.

The carbon footprint analysis of the current paper represented a bottom-up approach that used national EFs to comprehensively estimate Scope 1, 2 and 3 emissions. However, GHG emissions and material composition for most of the consumables and equipment were not made available by the manufacturer. To minimise missing data, GHG emissions were derived by estimating the main material components of the item and multiplying by national EFs that represented cradle-to-gate and grave emissions. A more comprehensive life cycle assessment that included the transport and packaging of equipment was not performed due to resource constraints and should be considered in future carbon footprint analyses.

CONCLUSION

Economic and GHG emission analyses are important for public policy and clinical practice decision making. Results from the scenario analyses give insight into the resource usage costs and GHG emissions per participant when implementing the m-PR program in metropolitan Sydney, Australia. For people with COPD who have adequate technology skills and live in a metropolitan area, mHealth PR presents a less costly and more environmentally friendly model, and there is the potential for greater savings for those who live in regional, rural or remote areas of Australia.

CHAPTER FIVE

DISCUSSION

MAIN FINDINGS

The study in **Chapter 2** was the first randomised controlled trial to compare an mHealth PR program with all essential and desirable components of PR [6] to centre-based PR (Figure 2.2). Results from this study showed that in people with moderate to severe COPD who had adequate technology skills, mHealth PR resulted in superior improvements in health status, as measured by the CAT score (MD -4.9 points), when compared to centre-based PR. The odds of a participant reaching the MCID for change in CAT score was five times greater if a participant was allocated to the mHealth PR group as opposed to the centre-based PR group. Superior improvements in health status may be explained by the enjoyment experienced by participants with performing exercises in the home environment and the ability to engage more effectively with education and self-management interventions.

In addition, the mHealth PR program was found to be equivalent to centre-based PR for improvements in exercise capacity (MD 13 m), with no between-group difference in the odds of a participant achieving the MCID of 30 m for the 6MWD. Equivalence was also demonstrated for improvements in HRQoL, dyspnoea and physical activity levels. Eighty participants completed at least one primary outcome (mHealth PR: n = 38 vs centre-based PR: n = 42) and exercise session adherence rates were equally as high in the mHealth PR (86%) and centre-based PR (87%) groups. However, more participants in the centre-based PR group required extensions to their PR program due to missed sessions, which were largely related to being medically unwell, public holiday periods and unspecified reasons, and highlight a possible advantage of mHealth PR overcoming certain barriers to access to and uptake of centre-based PR. The lack of serious adverse events related to the study demonstrated that mHealth PR can be safely delivered to people with COPD.

The study in **Chapter 3** was the first to comprehensively characterise engagement behaviour and adherence of people with COPD to an mHealth PR program. The results demonstrated that people with COPD had a high level of engagement and

adherence to the overall mHealth PR program and to the individual weekly tasks, presenting another possible explanation for why the mHealth PR group was superior to the centre-based PR group for improvements in health status as reported in Chapter 2. mHealth PR adherence (86%) rates were highest for the exercise sessions, and this was maintained across the eight-week program. Findings indicated that people with COPD were equally adherent to the endurance (84%) and resistance (87%) exercises and had moderately high adherence to the prescribed duration (76%) and repetitions (74%). Despite high overall engagement to the informational videos, a decline in engagement and adherence was seen over the eight-week program, more so with the videos that were repeated each week [232]. Adherence rates were low for daily tasks, such as the daily symptom questionnaire (13%) and daily step goals (50%). The requirement for daily task completion in addition to other mHealth PR interventions may be too laboursome for participants. Strategies such as automated synchronisation of activity monitor data or reducing the frequency of symptom questionnaires may mitigate this issue.

An understanding of the economic and environmental impacts of mHealth PR when compared to centre-based PR was necessary to evaluate the broad range of costs relating to the integration of mHealth PR into clinical practice, relevant not only to the healthcare system, but society more generally. The study in **Chapter 4** was the first to compare the resource usage costs and GHG emissions associated with mHealth PR to centre-based PR. A strength of the study was that the resource usage costs and GHG emissions associated with delivering the PR programs in research conditions, as well as in the scenario where programs were implemented into local clinical practice, were presented. This method allowed conclusions to be drawn on the clinical applicability of mHealth PR in both research and real-world clinical scenarios, ensuring a high degree of certainty and relevance with the results. When mHealth PR and centre-based PR were delivered in research conditions, there were no statistically significant differences between groups in per participant resource usage costs or GHG emissions. The results from the scenario analysis found that if the mHealth and centre-based PR programs were implemented into clinical practice within the NSLHD, mHealth PR would be associated with a statistically significant resource usage cost-saving of \$137 AUD and a reduction in GHG emissions of 36 kgCO₂e per participant. This would equate to a resource usage cost-saving of

\$58,088 AUD and a reduction in GHG emissions of 13,838 kgCO₂e over one year at two NSLHD PR sites for 375 participants. Resource usage cost-savings and reductions in GHG emissions were largely due to mHealth PR eliminating the need for participants to travel to and from PR sites for exercise sessions. As participants were recruited from metropolitan PR sites, distances from participant home addresses and PR sites were relatively short, at a mean 6.3 km one-way. This highlights the potential for greater cost-savings when delivering mHealth PR to people with COPD who live in regional, rural and remote areas, who must travel greater distances to access centre-based PR programs.

LIMITATIONS OF THE STUDIES

The limitations of the work presented in this thesis are discussed in each chapter. A general limitation is that due to the characteristics of the participants included in the studies, the findings from each chapter cannot be extended to people with mild or very severe COPD, people who require long-term oxygen therapy or those with limited English language skills. Participants had to be willing to partake in either the mHealth PR or centre-based PR programs, and as a consequence, the findings of this thesis cannot be generalised to people with COPD who are only willing or able to participate in one specific program. Participants were recruited from metropolitan PR sites and therefore, the results from this thesis may not apply to people with COPD who live in regional, rural or remote areas of Australia who have differing experiences in regard to access to healthcare [166, 167], disease severity [28] and prognosis [28]. In addition, a pragmatic approach was taken to recruitment and people with COPD were excluded if they did not have access to a smartphone or tablet device or had limitations to the use of technology. The research was also undertaken in the NSLHD, which services a relatively affluent area in a major capital city with a higher digital literacy index than the national average [298]. Consequently, most participants reported at least an adequate level of technology skills which may have introduced a sample bias towards people with higher digital literacy. Caution should be taken when applying the findings from this thesis to people with COPD who have lower levels of technology skills or who face limitations to the use of technology.

Beyond the limitations as detailed above, the main limitations for the randomised controlled trial in **Chapter 2** were related to the smaller sample size than anticipated,

and the centre-based PR group not achieving clinically significant improvements in health status and exercise capacity as might be expected. The sample size was smaller than expected as recruitment was undertaken whilst some PR sites were closed during the COVID-19 pandemic. In addition, sample size calculations did not account for multiple testing, and there was a higher proportion of missing data for the end-intervention 6MWD compared to the CAT score. Consequently, the study was likely underpowered which may limit the validity of the results. The findings that the centre-based PR group did not reach the MCID of 30 m [7] and 2 points [8], respectively, was surprising since the centre-based PR program followed Australian standards [3] and international clinical practice guidelines [73]. Recent high-quality studies investigating centre-based PR programs with two supervised sessions per week have reported similar results [172, 173, 175, 255], which may be related to people with COPD not performing the recommended three to five sessions of endurance training per week [64, 209]. People with COPD participating in centre-based PR in Australia are encouraged to perform unsupervised exercise sessions at home, outside of the two supervised sessions per week [3, 13]. There are doubts as to whether people with COPD adhere to these sessions [255] which could explain the difficulties in achieving clinically meaningful improvements in exercise capacity when delivering centre-based PR programs with two supervised sessions per week. There was insufficient data in the study in Chapter 2 to determine whether centre-based PR results were related to non-adherence to the unsupervised home-based sessions due to home exercise diaries only being completed by six (14%) centre-based PR participants. As a consequence, there was uncertainty as to whether adherence was low to filling in the paper-based diary or to performing the unsupervised exercise sessions. A final limitation was the potential for bias introduced by m-PR participants possibly receiving additional components within their PR program that were not available to CB-PR participants. Specifically, m-PR participants not only demonstrated high adherence to three exercise sessions per week but also received a physical activity intervention that was not delivered to the CB-PR group. Furthermore, due to COVID-19 pandemic restrictions and staffing constraints, some CB-PR participants were unable to access structured, group-based education sessions. The extent of CB-PR participants' engagement and adherence with face-to-face group-based and individualised education was not formally recorded, making it difficult to quantify differences in intervention exposure.

Nevertheless, findings from Chapter 3 and Chapter 4 suggest that, if m-PR participants did receive greater intervention dosage and additional program components, these were both achievable for people with COPD and associated with reduced resource usage costs and GHG emissions, highlighting a key benefit of mHealth PR when considering implementation of this model into clinical practice.

The main limitation to the study presented in **Chapter 3** was that mHealth PR participant adherence to the exercises and daily step goals were self-reported which may have been influenced by participants entering inaccurate data in the mHealth PR app. To overcome this, the system-recorded data was reviewed weekly by the physiotherapist and verified with participants during the weekly telephone calls. Minor technological issues may have disrupted use of the m-PR™ app; however, these issues were resolved quickly and remotely and likely had a minimal impact on system-record data.

There were some limitations to the study in **Chapter 4**. The resource usage costs and GHG emissions were determined using equipment and staffing levels specific to the five PR sites in NSLHD, Sydney, Australia. PR program structures, staffing wages, equipment use, and participant travel distances vary considerably between PR sites across Australia [15] and internationally [16]. Therefore, there are challenges in the generalisability of the findings from Chapter 4 to PR sites outside of NSLHD. To mitigate this, the cost units and GHG EFs used to calculate the resource usage costs and GHG emissions were outlined in detail to allow calculations to be made for other PR sites. Another limitation of the analysis was that it did not account for GHG emissions associated with equipment packaging and transport, with the baseline and end-intervention study assessments and with PR site maintenance, cleaning services and lighting. As a result, these findings may underestimate the total GHG emissions for both the mHealth and centre-based PR programs, although this difference is likely to be minimal.

IMPLICATIONS FOR CLINICAL PRACTICE AND SUGGESTIONS FOR FUTURE RESEARCH

The overall clinical implication from the studies in this thesis was that a comprehensive mHealth PR program, that includes all essential and desirable components of PR [6], could be offered as a possible management option to people

with moderate to severe COPD who possess adequate technology skills. This novel PR model presents a less costly and more environmentally sustainable alternative that improves clinical outcomes and supports people with COPD to be engaged and adherent to multiple PR program components such as education and self-management interventions. These findings align with recent international clinical practice guidelines [4, 74] which recommend that people with COPD be offered the option of telerehabilitation PR to improve access to PR and further adds to these guidelines by specifically supporting the effectiveness of mHealth PR. The primary clinical implications from each study presented in this thesis and suggested areas for future research are summarised in Figure 5.1.

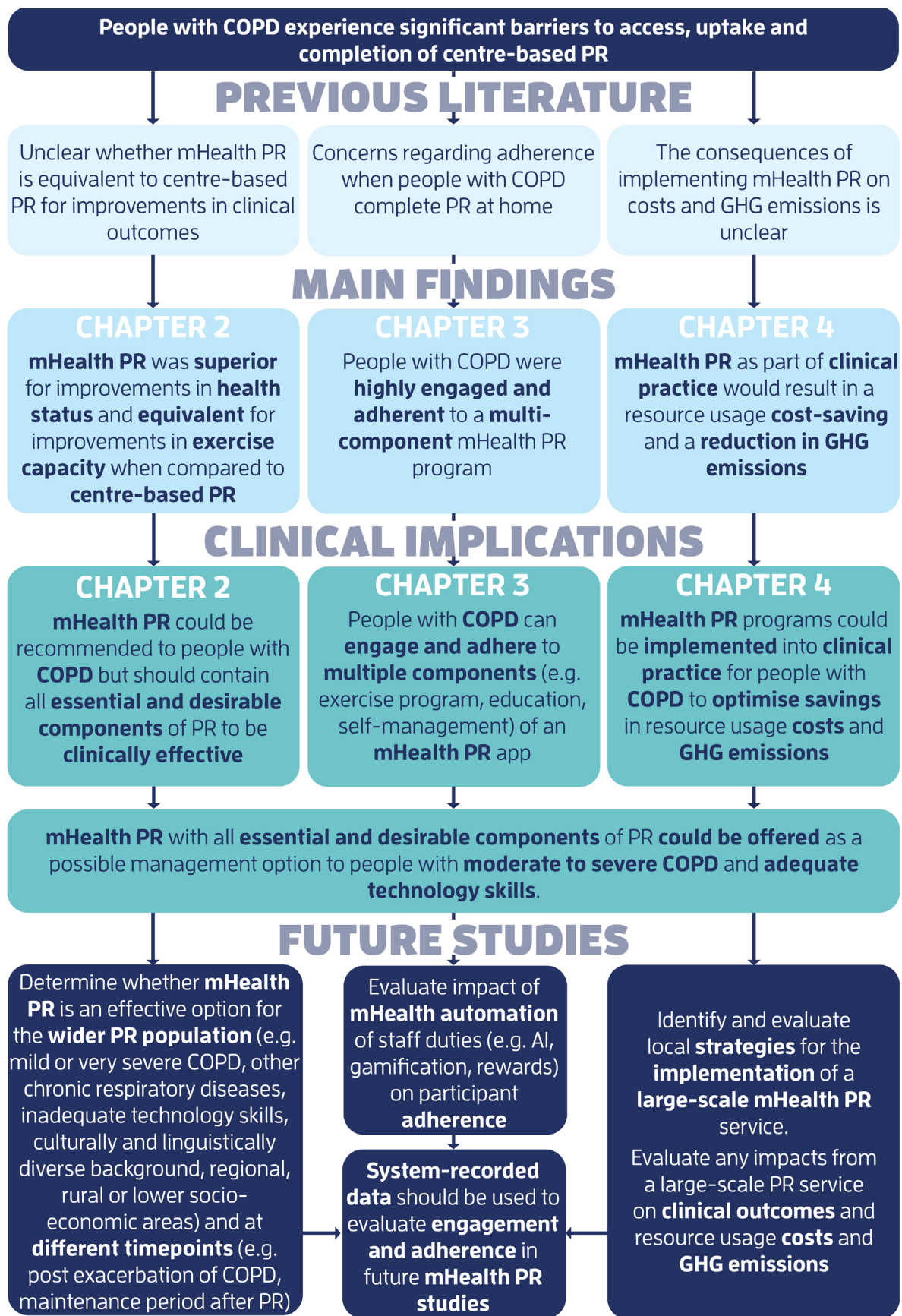


Figure 5.1. Summary of main findings and clinical implications. AI: artificial intelligence; COPD: chronic obstructive pulmonary disease; GHG: greenhouse gas; mHealth: mobile health; PR: pulmonary rehabilitation.

The main clinical implication of the study presented in **Chapter 2** was that mHealth PR can be recommended to people with moderate to severe COPD who have adequate technology skills, provided that it includes all essential and desirable components of PR [6] to ensure effectiveness on clinical outcomes. Improving access to PR has been identified as a key action area in national [178] and international [5, 74, 299] policy statements. By enabling PR to be delivered in the home environment, mHealth PR may address certain barriers to access, uptake and completion of PR [5] as it delivers a PR program without requiring additional PR centre-based space and eliminates the need for participants to travel to and from PR sites. Other studies have demonstrated it is feasible to deliver mHealth PR to people with COPD who are unable or unwilling to attend centre-based PR [212, 214], or who prefer mHealth PR [220, 223]. To increase the reach of these benefits, further research is needed to evaluate the effectiveness of mHealth PR, with the essential and desirable components of PR, in the wider population of people who attend PR, such as those with mild or very severe COPD, other chronic respiratory diseases, people who live in regional, rural, remote or lower socio-economic areas, where lived experiences of COPD, healthcare access and digital literacy index may differ [166, 167]. Future mHealth PR programs should also evaluate culturally appropriate programs for people who are culturally and linguistically diverse and First Nations people. Additionally, further research is needed to determine whether mHealth PR delivered at different timepoints, such as following hospital discharge for an exacerbation of COPD or during the maintenance period after PR, would result in similar improvements in clinical outcomes. Delivering mHealth PR post-hospital discharge could prove to be an effective and feasible strategy to provide the program to people with COPD whilst addressing the recent Australian COPD Clinical Care Standards [157] that recommend that people with COPD should commence PR within four weeks of hospital discharge.

The inclusion of education and self-management interventions within PR programs is inconsistently recommended across clinical guidelines [3, 4, 6, 74]. Participant experiences, presented quantitatively in **Chapter 2** and explored qualitatively in a separate published manuscript [244], highlighted the perceived value of structured and individualised education and self-management components among m-PR participants. As discussed in Chapter 2, these perceived benefits may help explain

the greater improvements in health status observed in the m-PR group compared to the CB-PR group. Studies evaluating mHealth PR programs with integrated self-management components [212, 215] and self-management mHealth apps [251-254] have similarly demonstrated significant improvements in self-efficacy. In contrast, there remains limited evidence that education alone [60], or when combined with centre-based PR [117, 118], sufficiently improves self-efficacy. The delivery of education and self-management interventions through mHealth PR apps, shown to be well engaged with in **Chapter 3**, may enhance outcomes in knowledge and self-efficacy more effectively than traditional face-to-face delivery. Further research is needed to determine which specific features of mHealth PR apps most effectively optimise improvements in knowledge and self-efficacy, and future iterations of clinical guidelines should consider these findings when recommending which components are essential to PR.

A clinical implication from the study in **Chapter 3** was that people with moderate to severe COPD and adequate levels of technology skills can be expected to engage and adhere highly to multiple interventions delivered through an mHealth PR app, addressing previous concerns [185, 186] regarding low adherence to unsupervised PR programs delivered in the home environment. Conversely, the findings indicated that people with COPD were highly adherent to an exercise program of three sessions per week, achieving guideline recommendations for PR exercise frequency [64, 209], whilst also engaging with other program components such as education, symptom monitoring questionnaires and daily step goals. Increasing the frequency of centre-based PR exercise sessions and/or allowing for additional time to deliver program components other than the exercise program would have repercussions on resource usage costs and GHG emissions, as demonstrated in **Chapter 4**. This strategy may not be feasible for some PR sites already operating at maximal capacity and highlights the advantages of implementing mHealth PR alone, or in combination with, centre-based PR.

The Lung Foundation Australia's national PR strategy framework [178] has called for the establishment of real-time data collection systems to evaluate outcomes of PR program against national standards and to reduce variations in care. The ability to automate data collection through mHealth PR system-recorded data, as described in **Chapter 3**, enabled a centralised database that facilitated a comprehensive analysis

of engagement and adherence. The potential to integrate mHealth PR automated data with electronic medical records or national databases could transform the way PR programs in Australia are monitored and ensure effective models of PR are delivered nationwide. Future mHealth PR studies should evaluate the feasibility, security and clinical impact of such integration to support scalable improvements in PR delivery.

In addition, the study in **Chapter 3** demonstrated that automated data collection was achievable without placing additional demands on staff time. As identified in **Chapter 4**, the majority of healthcare provider resource usage costs were attributed to staff wages, indicating that the implementation of strategies to reduce staff time could lead to greater resource usage cost savings. The integration of computer algorithms or artificial intelligence may help to further reduce the staff time required for mHealth PR interventions, such as the prescription and progression of exercise programs and physical activity goals, recommendations for medication action plan use in response to changes in symptom questionnaires or vital sign observations, and providing motivation. Other automated strategies, such as gamification and loyalty rewards, could be used to replace or supplement the motivation provided by staff during regular telephone calls, and has shown some promise in maintaining adherence in self-management mHealth apps for other chronic diseases [300, 301]. However, automating staff duties carries the risk of compromising adherence, as evident by low exercise adherence in mHealth PR studies [16, 214, 220, 227] that lacked regular motivational calls, even when automation was used for exercise program prescription and progression [214]. Future studies should evaluate these approaches to automating staff duties and should utilise system-recorded data from mHealth PR apps as a comprehensive and effective method for monitoring their impact on participant engagement and adherence levels.

The main clinical implication from **Chapter 4** was that mHealth PR could be implemented into clinical practice for people with moderate to severe COPD who have adequate technology skills to increase savings in resource-usage costs and GHG emissions. The differences in results between the base and scenario analyses indicate that the expansion of mHealth PR programs to a larger cohort would result in greater savings in resource usage costs and GHG emissions. In particular, larger savings per mHealth PR participant were found when sharing app server costs and

GHG emissions across more participants, and has similarly been shown in real-world scenarios with mHealth PR app licensing costs in the UK [233]. One strategy to scaling mHealth PR to a larger cohort would involve implementing a central mHealth PR service across multiple PR sites or across large health jurisdictions. This approach would additionally have the benefit of increasing the accessibility of PR to people who live in regional, rural and remote areas without a local PR program. However, in this model, implementation challenges such as staff training needs, user adoption and integration into existing electronic health records will likely have a greater impact on implementation success and should be evaluated in future studies.

Remote PR assessments supported by digital technologies would allow a central mHealth PR service to deliver programs to people with COPD across health districts and state borders. Remote exercise tests have been deemed safe and reliable [296, 297, 302, 303], and recently proven feasible in an mHealth PR study [214] and questions whether centre-based assessments are essential to PR [6]. Eliminating the need for participants to travel to and from PR sites for assessments, particularly for those in regional, rural and remote areas of Australia who travel further to access healthcare [166, 167], would further lower resource usage costs and GHG emissions associated with participant travel, which was highlighted in **Chapter 4** as a major contributing factor. However, centre-based assessments internationally are considered essential in guiding clinically effective exercise prescription and progression [6, 74]. Further research is needed to evaluate the effects of a completely remote, large-scale mHealth PR program on clinical outcomes and adherence rates in people with COPD, and the associated resource usage costs and GHG emissions.

There is disparity between the time to conduct mHealth randomised controlled trials and the rapid pace of digital technology innovations [304]. As an example, data collection for the studies in this thesis took 28 months to complete, comparable to other mHealth randomised controlled trials [305], over which time the activity monitor provided to participants in the study in **Chapter 2** became commercially unavailable. Emerging technologies, such as the introduction of 5G and enhanced smartphone capabilities, are driving significant change in the mobile technology landscape that will outpace current mHealth research. Compounding this, the translation of research into clinical practice is estimated to take 17 years [306]. A delay in the translation of

mHealth PR research into public health clinical practice has led to the development of numerous commercial mHealth PR programs internationally [234, 235, 307], some unsupported by research, and has subsequently raised concerns regarding the quality and standardisation of these programs [235, 308]. The findings from the studies in this thesis suggest that the timely implementation of evidence-based mHealth PR into clinical practice could be supported by policymakers to maximise the benefits of PR for people with COPD.

CONCLUSIONS

mHealth PR is a safe and appears to be a clinically effective option for people with moderate to severe COPD who have adequate technology skills. mHealth PR can be used to deliver a multi-component PR program that is well engaged with, and presents as a less costly and more environmentally sustainable alternative to centre-based PR. Overall, the series of studies in this thesis have demonstrated that mHealth PR, encompassing all essential and desirable components of PR, could be offered as a viable option for people with COPD. There is an urgent need to translate mHealth PR research findings into clinical practice and future studies should evaluate the effectiveness and consequences of implementation strategies for the timely adoption of large-scale mHealth PR services.

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APPENDICES

Appendix 1. Randomised controlled trials evaluating the effects of videoconferencing PR in people with COPD.

Author (Year), Country, FEV ₁ % pred, N (IG/CG)	Essential PR, PEDro	Intervention Program	Comparison Program	Between-Group Results
Cox [172] (2021) Australia <u>FEV₁% pred</u> (SD): IG = 59% (25) CG = 63% (26) N: 71 / 71	<u>PR</u> : 12 <u>PEDro</u> : 8	IG : videoconferencing PR. 2 x 30-60 min group-based exercise sessions and 3 unsupervised walking sessions.week ⁻¹ . 8 weeks. Group-based and individualised education and self-management training via videoconferencing platform. Printed and online education resources.	CG : centre-based PR. 2 x 30-60 min supervised, group-based exercise sessions and 3 unsupervised walking sessions.week ⁻¹ . 8 weeks. Group-based and individualised education and self-management training in person. Printed and online education resources.	MD (95% CI) Ex capacity : 6MWD : -6 (-26 to 15) m Health status n.m HRQoL : CRQ total : -2.6 (-9.0 to 3.7) points Dyspnoea : CRQ-D : -1 (-3 to 1) points; mMRC : 0 (-0.3 to 0.3) points PA : LPA : -22 (-61 to 17) min; MVPA : -2 (-18 to 14) min Self-efficacy : PRAISE : 1 (-1 to 3) points AE : No AE related to trial. Hospitalisation : <u>IG</u> : 4 vs <u>CG</u> : 2 Technology : n = 42% required assistance with technological issues Adherence : Exercise : <u>IG</u> : 84% vs <u>CG</u> : 79% Engagement : Education : <u>IG</u> : 97%* vs <u>CG</u> : 84% Economic : 95% probability IG equivalent to CG for cost-effectiveness Environment : <u>IG</u> : 30 kgCO ₂ e vs <u>CG</u> : 70kgCO ₂ e, p<0.001
Hansen [173] (2020) Denmark <u>FEV₁% pred</u> (SD): IG = 33% (10) CG = 34% (8) N: 67 / 67	<u>PR</u> : 12 <u>PEDro</u> : 7	IG : videoconferencing PR. 3 x 35 min group-based exercise sessions.week ⁻¹ . 10 weeks. Weekly group-based education sessions (3 x 20 min) via videoconferencing platform	CG : 10–12-week centre-based PR. 2 x 60 min supervised group-based exercise sessions.week ⁻¹ . Weekly group-based education session (1 x 60 – 90 min) in person	MD (95% CI) Ex capacity : 6MWD : 6 (-10 to 23) m Health status CAT : 1.4 (-0.1 to 3.0) points HRQoL : CCQ total : -0.2 (-0.1 to 0.4) points Dyspnoea : n.m PA : Daily steps : -283 (-845 to 278) steps Self-efficacy : n.m AE : Minor : <u>IG</u> : 0 vs <u>CG</u> : 2. No serious AE Technology : Major : 0.5% sessions. Minor : 14% sessions Adherence : Exercise : <u>IG</u> : 73% vs <u>CG</u> : 63%. More completers in IG (OR [95% CI]: 3.18 [0.78 to 3.37])* Engagement : n.m Economic : n.m Environment : n.m

Appendix 1 cont.

<p>Tsai [208] (2017) <u>Australia</u> <u>FEV1% pred (SD):</u> IG = 60% (23) CG = 68 (19) <u>N: 20 / 17</u></p>	<p><u>PR: 13</u> <u>PEDro: 8</u></p>	<p>IG: videoconferencing PR. 3 x 60 min group-based sessions.week⁻¹. 8 weeks. No education program.</p>	<p>CG: Standard care and medication action plan. No education program.</p>	<p>MD (95% CI) Ex capacity: ESWT: 340 (153 to 526)* s Health status CAT: -3 (-7 to 0) points HRQoL: CRQ total: 8 (-1 to 16) points Dyspnoea: CRQ-D: 3 (-0.5 to 6) points PA: Daily steps: 475 steps (-200 to 1151) Self-efficacy: PRAISE: 8 (2 to 14)* points AE: No AE Technology: 12% of sessions Adherence: Exercise: mean [SD] 22 [5] session. 22 / 24 sessions = 92% Engagement: n.m Economic: n.m Environment: n.m</p>
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*statistically significant between-group difference. Essential PR is the total number of essential PR components [6] that were included in the intervention group out of 13 possible essential components. PEDro scale [228] is a measure of the methodological quality of clinical trials and is a score out of 10. 6MWD: six-minute walk distance; CAT: COPD Assessment Test; CCQ: Clinical COPD Questionnaire; CI: confidence interval; CG: comparison group; CRQ: Chronic Respiratory Disease Questionnaire; CRQ-D: CRQ Dyspnoea score; ESWT: endurance shuttle walking test; Ex: exercise; FEV1%pred: percent predicted forced expiratory volume in one second; HRQoL: health-related quality of life; IG: intervention group; m: metres; MD: mean difference; min: minutes; N: number of participants recruited; n.m: not measured; PA: physical activity; PEDro: Physiotherapy Evidence Database; PR: pulmonary rehabilitation; PRAISE: Pulmonary Rehabilitation Adapted Index of Self-Efficacy; s: seconds; SD: standard deviation.

Appendix 2. Randomised controlled trials investigating the effects of web-based PR in people with COPD.

Author (Year), Country, FEV ₁ % pred, N (IG/CG)	Essential PR, PEDro	Intervention Program	Comparison Program	Between-Group Results
Chaplin [196] (2017) UK <u>FEV₁% pred (SD):</u> IG = 59% (29) CG = 55% (21) <u>N: 51 / 52</u>	<u>PR:</u> 12 <u>PEDro:</u> 5	IG: 11-week web-based PR. 5 unsupervised exercise sessions.week ⁻¹ . Education content (text and videos) and self-management tasks (goal setting and monitoring, symptom diary) on website.	CG: centre-based PR (2 x 60 min supervised group-based exercise sessions.week ⁻¹) for 4 weeks. Unsupervised home-based PR for 3 weeks. Group-based (2 x 60 min) self-management education sessions for 4 weeks.	MD (SD). No data for between-group MD or p-value Ex capacity: ESWT: <u>IG:</u> 189 (211) s vs <u>CG:</u> 185 (247) s Health status CAT: no significant difference', no data reported HRQoL: CRQ-D: <u>IG:</u> 0.7 (1.2) points vs <u>CG:</u> 0.8 (1.0) points Dyspnoea: CRQ-D: <u>IG:</u> 0.7 (1.2) points vs <u>CG:</u> 0.8 (1.0) points PA: n.m Self-efficacy: n.m AE: n.m Technology: n.m Adherence: n.m Engagement: n.m Economic: n.m Environment: n.m
Nguyen [194] (2008) USA <u>FEV₁% pred (SD):</u> IG = 50% (18) CG = 49% (217) <u>N: 20 / 19</u>	<u>PR:</u> 11 <u>PEDro:</u> 6	IG: web-based PR. 4 x 30 min unsupervised exercise sessions.week ⁻¹ . 6 months. Individual face-to-face education (60-90 min), structured interactive education on website (6 x 60 min session), web-based and mobile app diary, and live group chat sessions on website.	CG: telephone home-based PR. 4 x 30 min unsupervised exercise sessions.week ⁻¹ . 6 months. Individual face-to-face education (60-90 min), structured face-to-face group-based education sessions (6 x 60 min session) and paper education modules and diary.	6 months MD (SD). No data for between-group MD Ex capacity: 6MWD: <u>IG:</u> 456 (91) m vs <u>CG:</u> 394 (165) m Health status n.m HRQoL: CRQ total: <u>IG:</u> 100 (17) points vs <u>CG:</u> 95 (23) points Dyspnoea: CRQ-D: <u>IG:</u> 21 (6) points vs <u>CG:</u> 20 (6) points PA: n.m Self-efficacy: Self-efficacy score (0-10): <u>IG:</u> 7 (3) points vs <u>CG:</u> 5 (4) points AE: n.m. Total of 11 exacerbations Technology: Several significant issues causing trial to stop early Adherence: Education: <u>IG:</u> 96% vs <u>CG:</u> 80% Engagement: Highest to exercise and symptom entries and education sessions, low to exercise goal setting, alerts Economic: n.m Environment: n.m

Appendix 2. cont.

<p>Nguyen [195] (2013) <u>USA</u> <u>FEV₁ %pred (SD):</u> IG 1 = 53% (20) IG 2 = 51% (18) CG = 49% (20) <u>N: 43 / 41 / 41</u></p>	<p><u>PR: 11</u> <u>PEDro: 6</u></p>	<p>IG 1: web-based PR. 4 x 30 min unsupervised exercise sessions.week⁻¹. 12 months. Individual face-to-face education (60-90 min), structured interactive education on website (6 x 60 min session), web-based and mobile app diary, and live group chat sessions on website.</p> <p>IG 2: telephone home-based PR. 4 x 30 min unsupervised exercise sessions.week⁻¹. Individual face-to-face education (60-90 min), structured face-to-face group-based education sessions (6 x 60 min session) and paper education modules and diary.</p>	<p>CG: home-based education alone. 12 months. Monthly, face-to-face education classes, paper education material and bi-weekly phone calls with general health information</p>	<p>12 months mean (95% CI). Between-group statistical difference compared across all 3 groups. No data for between-group MD</p> <p>Ex capacity: 6MWD: <u>IG 1:</u> 431 (394 to 468) m vs <u>IG 2:</u> 425 (386 to 464) m vs <u>CG:</u> 418 (386 to 451) m.</p> <p>Health status n.m HRQoL: CRQ total: <u>IG 1:</u> 105 (98 to 112) points vs <u>IG 2:</u> 96 (89 to 104) points vs <u>CG:</u> 98 (91 to 106) points</p> <p>Dyspnoea: CRQ-D: <u>IG 1:</u> 26 (24 to 28) points vs <u>IG 2:</u> 23 (21 to 25) points vs <u>CG:</u> 24 (22 to 26) points</p> <p>PA: n.m</p> <p>Self-efficacy: Self-efficacy score (0-10): <u>IG 1:</u> 7 (6 to 8) points vs <u>IG 2:</u> 6 (5 to 7) points vs <u>CG:</u> 6 (5 to 7) points</p> <p>AE: n.m</p> <p>Technology: n.m</p> <p>Adherence: Exercise: Duration and frequency no different between groups</p> <p>Engagement: n.m</p> <p>Economic: n.m</p> <p>Environment: n.m</p>
<p>Wang [193] (2017) <u>China</u> <u>GOLD III-IV:</u> IG: n = 40 (73%) CG: n = 52 (80%) <u>N: 62 / 68</u></p>	<p><u>PR: 10</u> <u>PEDro: 6[†]</u></p>	<p>IG: web-based PR (session frequency not specified). 12 months. Disease-specific and individualised education content on website.</p>	<p>CG: Standard care.</p>	<p>12 months mean (SD). No data for between-group MD.</p> <p>Ex capacity: 6MWD: <u>IG:</u> 297 (113)* m vs <u>CG:</u> 199 (99) m</p> <p>Health status n.m HRQoL: SGRQ Total: <u>IG:</u> 31 (21)* points vs <u>CG:</u> 58 (2) points</p> <p>Dyspnoea: mMRC: <u>IG:</u> 1.1 (1.0)* points vs <u>CG:</u> 2.9 (0.9) points</p> <p>PA: n.m</p> <p>Self-efficacy: n.m</p> <p>AE: n.m</p> <p>Adherence: n.m</p> <p>Engagement: n.m</p> <p>Economic: n.m</p> <p>Environment: n.m</p>

Appendix 2. cont.

<p>Zanaboni [211] (2022) <u>Norway, Australia, Denmark</u> <u>FEV₁% pred (SD):</u> IG 1 = 40% (17) IG 2 = 45% (17) CG = 40% (16) <u>N: 40 / 40 / 40</u></p>	<p><u>PR: 13</u> <u>PEDro: 7</u></p>	<p>IG 1: web-based PR. videoconferencing calls for individualised education, self-management intervention (symptom and exercise diary, goal setting) and/or exercise supervision. 3-5 x 60 min unsupervised exercise sessions.week⁻¹. 8-week intensive PR followed by 22 months maintenance.</p>	<p>CG: Standard care.</p>	<p>24 months mean (SD). Between-group statistical differences compared IG 1 to CG or IG 2 to CG. No data for between-group MD Ex capacity: 6MWD: <u>IG 1:</u> 400 (142) m, <u>IG 2:</u> 460 (126)* m vs <u>CG:</u> 357 (102) m Health status CAT: <u>IG 1:</u> 19 (7) points, <u>IG 2:</u> 18 (9)* points vs <u>CG:</u> 20 (7) points HRQoL: EQ-5D VAS: <u>IG 1:</u> 55 (22) points, <u>IG 2:</u> 58 (21)* points vs <u>CG:</u> 50 (21) points Dyspnoea: mMRC: <u>IG 1:</u> 1.9 (1.2) points, <u>IG 2:</u> 1.5 (1.1)* points vs <u>CG:</u> 2.3 (1.1) points PA: n.m AE: no AE related to study Self-efficacy: GSES: <u>IG 1:</u> 30 (6) points, <u>IG 2:</u> 31 (5) points vs <u>CG:</u> 33 (6) points Adherence: n.m Engagement: n.m Economic: n.m Environment: n.m</p>
		<p>IG 2: home-based PR. 3-5 x 60 min unsupervised exercise sessions.week⁻¹. Paper diary and self-management education. 24 months.</p>		

*statistically significant between-group difference. Essential PR is the total number of essential PR components [6] that were included in the intervention group out of 13 possible essential components. PEDro scale [228] is a measure of the methodological quality of clinical trials and is a score out of 10.

†PEDro score not previously completed and was calculated for this table with the following results: Eligibility criteria: Yes; Random allocation: Yes; Concealed allocation: Yes; Baseline comparability: Yes; Blind subjects: No; Blind therapists: No; Blind assessors: No; Adequate follow-up: Yes; Intention-to-treat analysis: No; Between-group comparisons: Yes; Point estimates and variability: Yes. Note: Eligibility criteria item does not contribute to total score
 6MWD: six-minute walk distance; AE: adverse event; CAT: COPD Assessment Test; CI: confidence interval; CG: comparison group; CRQ-D: Chronic Respiratory Disease Questionnaire dyspnoea domain; ESWT: endurance shuttle walking test; EQ-5D VAS: European Quality of Life five dimensions five levels visual analogue scale; Ex: exercise; FEV₁%pred: percent predicted forced expiratory volume in one second; GOLD: The Global Initiative for Chronic Obstructive Lung Disease spirometry criteria for airflow limitation severity; GSES: Generalised Self-Efficacy Scale; IG: intervention group; MD: mean difference; mMRC: modified Medical Research Council dyspnoea scale; N: number of participants recruited; n.m: not measured; PA: physical activity; PEDro: Physiotherapy Evidence Database; Post: post-intervention; PR: pulmonary rehabilitation; SD: standard deviation.

Appendix 3. Clinical trials investigating the effects of mHealth PR in people with COPD (non-randomised controlled trials).

Author (Year), App Name, Country, FEV ₁ % pred, N (IG/CG), Essential PR,	Study Design	Intervention Program	Comparison Program	Between-Group Results
Cooper [221] (2022) 'myCOPD' UK <u>FEV₁ %pred: N/A</u> <u>N: 113</u> <u>PR: 1</u>	Single-arm observational study	IG: mHealth app with optional PR. <u>Education:</u> Education and inhaler videos on app. <u>Self-management:</u> Medication diary and action plan on app.	No comparison group	Proportion of participants (%) Ex capacity: n.m Health status: n.m HRQoL: n.m Dyspnoea: n.m PA: n.m Self-efficacy: n.m AE: n.m Technology: n.m Adherence: n.m Engagement: n = 79% activated app. n = 57% recorded CAT >1 times. n = 39% initiated PR module. n = 24% watched educational videos. n = 10% watched >1 inhaler video. Economic: n.m Environment: n.m
Deng [222] (2021) 'WeChat' China <u>FEV₁ %pred (SD):</u> 47% (16) <u>N: 12</u> <u>PR: 11</u>	Feasibility single-arm pilot-study	IG: mHealth PR. 3-7 x 10-60 mins unsupervised sessions.week ⁻¹ . 12 weeks. <u>Education:</u> Nil. <u>Self-management:</u> Nil.	No comparison group	MD only Ex capacity: 6MWD: 26 m* Health status: CAT: -3 points* HRQoL: CCQ: -2 points* Dyspnoea: "mMRC grades reduced overall" no statistical analysis PA: n.m Self-efficacy: n.m AE: n.m Technology: reports some but no data Adherence: Exercise: 82%. Remained high over time Engagement: n.m Economic: n.m Environment: n.m

Appendix 3. cont.

<p>Rassouli [224] (2018) 'Kaia COPD' Germany, Austria, Switzerland FEV₁ %pred: N/A N: 56 PR: 7</p>	<p>Single-arm observational study</p>	<p>IG: mHealth PR. No comparison group. 7 unsupervised sessions.week⁻¹. 20 days. <u>Education:</u> Inhaler videos and education on app. <u>Self-management:</u> Symptom monitoring.</p>	<p>Mean (SD) Ex capacity: n.m Health status: CAT: Pre: 22 (8) points vs Post: 19 (8)* points HRQoL: CRQ: significant improvement in all domains* Dyspnoea: CRQ-D: Pre: 3.4 (1) points vs Post: 3.2 (1)* points PA: n.m Self-efficacy: n.m AE: n.m Technology: n = 16% activated app out of Adherence: n.m Engagement: n.m Economic: n.m Environment: n.m</p>
<p>Whittaker [225] (2021) 'mPR' New Zealand GOLD II: n = 14 (54%) N: 13 PR: 11</p>	<p>Single-arm pilot study</p>	<p>IG: mHealth PR. No comparison group. 5 unsupervised sessions.week⁻¹. 9 weeks. <u>Education:</u> Educational text messages, education video on app. <u>Self-management:</u> Medication action plan.</p>	<p>Proportion of participants (%) Ex capacity: n.m Health status: n.m HRQoL: n.m Dyspnoea: n.m PA: n.m Self-efficacy: n.m AE: no AE related to study. 1 x minor knee pain. Technology: n.m Adherence: Exercise video: 88 times out of expected 297 times. Engagement: n = 69% accessed app once. Days app used mean 13.3 days (range 1 to 27). Most viewed module was medication action plan. n = 100% completed CAT score. Economic: n.m Environment: n.m</p>

Appendix 3. cont.

<p>Yonchuk [226] (2021) ‘Respercise’ <u>USA, UK, Germany</u> <u>FEV₁ %pred: N/A</u> <u>N: 96</u> <u>PR: 9</u></p>	<p>Feasibility trial alongside pharmaceutical RCT</p>	<p>IG: intervention pharmaceutical drug with mHealth PR. 5 unsupervised sessions.week⁻¹. 13 weeks. <u>Education:</u> Education modules on app. <u>Self-management:</u> Exercise and physical activity diary.</p>	<p>CG: Placebo pharmaceutical drug with mHealth PR. 5 unsupervised sessions.week⁻¹. 13 weeks.</p>	<p>MD (SE) Ex capacity: 5STS: females -2.2 (0.7) s, males -2.3 (0.6) s Health status: n.m HRQoL: n.m Dyspnoea: n.m PA: n.m Self-efficacy: n.m AE: n = 3 participants experienced technological issues Technology: n.m Adherence: Exercise: n = 70% Engagement: Daily step entries: n = 90% Economic: n.m Environment: n.m</p>
<p>Barata [219] (2022) ‘Pneumocontrol’ <u>Romania</u> <u>FEV₁ %pred:</u> IG = 42% (5) CG = 42% (5) <u>N: 58 / 72</u> <u>PR: 12</u></p>	<p>Controlled clinical trial</p>	<p>IG: mHealth PR. 5 x 40-60 mins sessions.week⁻¹. 3 weeks.</p>	<p>CG: inpatient PR. 5 x 40-60 mins sessions.week⁻¹. 3 weeks.</p>	<p>MD (SD) Ex capacity: 6MWD: <u>IG:</u> 44 (6)[#] m vs <u>CG:</u> 31 (5) m Health status: CAT: <u>IG:</u> 6.2 (0.8)[#] points vs <u>CG:</u> 4.8 (1) points HRQoL: n.m PA: n.m AE: n.m Technology: n.m Adherence: n.m Engagement: n.m Economic: n.m Environment: n.m</p>

Appendix 3. cont.

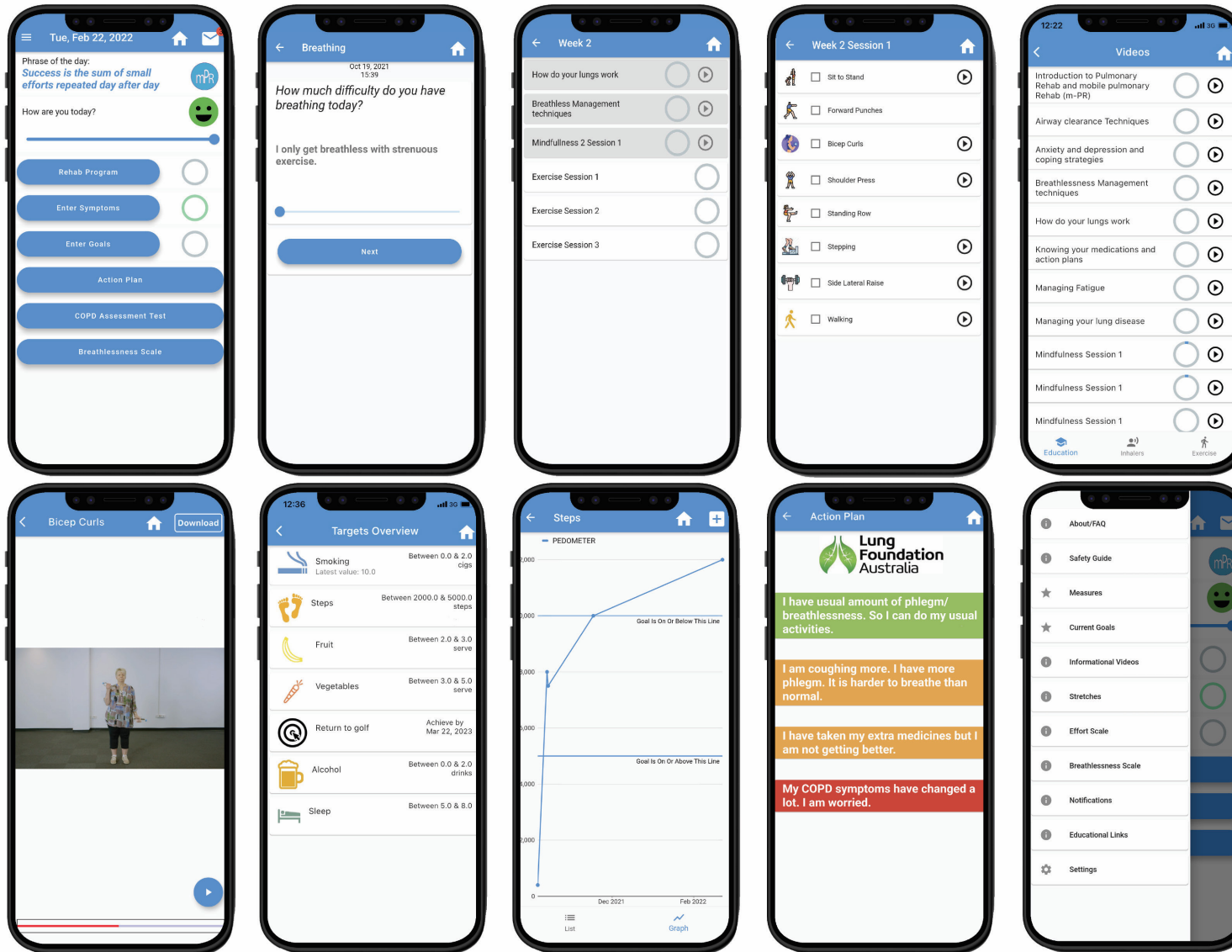
<p>Candy [220] (2023) ‘mPR’ New Zealand <u>FEV₁ %pred</u>: N/A <u>N</u>: 38 / 67 (COPD = 61%) <u>PR</u>: 13</p>	<p>Controlled clinical trial</p>	<p>IG: mHealth PR. 5 x 40-60 min unsupervised sessions.week⁻¹, 8-12 weeks. <u>Education</u>: Described as ‘education’ but not specified. <u>Self-management</u>: Described as ‘behaviour change intervention’ but not specified.</p>	<p>CG: centre-based PR (videoconferencing PR or home-based PR due to COVID-19). 2 x 60-90 min sessions.week⁻¹, 8-12 weeks. <u>Education</u>: See below. <u>Self-management</u>: Face-to-face self-management education.</p>	<p>MD (95% CI) Ex capacity: n.m Health status: CAT: 0.7 (-2.0 to 3.4) points HRQoL: EQ-5D VAS: 7.4 (-1.0 to 15.6) points Dyspnoea: mMRC: -0.5 (-0.8 to -0.1) points PA: n.m Self-efficacy: n.m AE: one serious AE in IG (fall) Technology: n.m Adherence: Exercise: <u>IG</u>: 53% vs <u>CG</u>: 75%. Engagement: n = 87% engaged. n = 76% still engaged at 8 weeks. Dashboard opened 8593 times, videos 1038 times (all participants) Economic: n.m Environment: n.m</p>
<p>Flynn [223] (2025) ‘Health in motion’ USA <u>FEV₁ %pred (SD)</u>: IG = 54% (3) CG = 49% (3) <u>N</u>: 27 / 21 <u>PR</u>: 11</p>	<p>Controlled clinical trial</p>	<p>IG: mHealth PR. 3-5 x 60 min unsupervised sessions.week⁻¹. 6-8 weeks. <u>Education</u>: avatar guided education modules on app. <u>Self-management</u>: medication action plan and health diary on app.</p>	<p>CG: centre-based PR. 2 x 30-60 min supervised sessions.week⁻¹ and 1 unsupervised session.week⁻¹. 6-8 weeks. <u>Education</u>: 30-60 min education classes. <u>Self-management</u>: Nil.</p>	<p>MD (SD) Ex capacity: 6MWD: <u>IG</u>: 34 (50) m vs <u>CG</u>: 48 (47) m Health status: CAT: <u>IG</u>: 3 (6) points vs <u>CG</u>: 4 (4) points HRQoL: SGRQ Total: <u>IG</u>: 7 (11) points vs <u>CG</u>: 9 (14) points Dyspnoea: n.m PA: n.m Self-efficacy: n.m AE: no AE Technology: technological issues, some resulting in drop out Adherence: Exercise: <u>IG</u> = 87% vs <u>CG</u> = 94%. App access: 150% of expected days Engagement: <u>IG</u>: 25 (12) hours used. 36 (14) days app accessed Economic: n.m Environment: n.m</p>

Appendix 3. cont.

<p>Zhang [227] (2022) ‘Xeek’ China <u>FEV₁ %pred (SD):</u> IG 1 = 42% (12) CG = 43% (12) <u>N:</u> 67 / 38 <u>PR:</u> 13</p>	<p>Cohort study</p>	<p>IG: mHealth PR. 2-3 supervised sessions followed by 5 unsupervised sessions.week⁻¹. 12 weeks. <u>Education:</u> Nil. <u>Self-management:</u> exercise, lung function and vital sign diary</p>	<p>Participants grouped by adherence after completion of intervention. Lowest adherence group (<1 week of exercise) used as control.</p>	<p>Compared outcomes based on exercise adherence Ex capacity: 6MWD: Significantly higher when adherence > 8 weeks Health status: CAT: Significantly lower when adherence > 8 weeks HRQoL: No significant difference regardless of adherence Dyspnoea: mMRC: Significantly lower when adherence > 8 weeks PA: n.m Self-efficacy: n.m AE: No serious AE Technology: n.m Adherence: n = 20% completed 12-week program. 43% >8 weeks Engagement: n.m Economic: n.m Environment: n.m</p>
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*statistically significant within-group difference. #statistically significant between-group difference. PR score is the total number of essential PR components [6] that were included in the intervention group out of a possible 13 essential components. 5STS: five-times sit-to-stand tests; 6MWD: six-minute walk distance; AE: adverse event; CAT: COPD Assessment Test; CCQ: Clinical COPD Questionnaire; CG: comparison group; CRQ-D: Chronic Respiratory Disease Questionnaire dyspnoea domain; education component of program; EQ-5D VAS: European Quality of Life five dimensions five levels visual analogue scale; FEV₁%pred: percent predicted forced expiratory volume in one second; GOLD: The Global Initiative for Chronic Obstructive Lung Disease spirometry criteria for airflow limitation severity; IG: intervention group; m: metres; MD: mean difference; mMRC: modified Medical Research Council dyspnoea scale; N: number of participants recruited; N/A: not available; n.m: not measured; PA: physical activity; PR: pulmonary rehabilitation; s: seconds; SD: standard deviation; self-management intervention provided to participants; SGRQ: St George Respiratory Questionnaire; USA: United States of America.

Appendix 4. Examples of m-PR™ app screens.



Appendix 5. Components of the m-PR program.

Program component	Description
Exercise program	<p>Participants each week received three exercise sessions which included endurance and resistance exercises. Participants could view each exercise, an informational exercise video, and the prescribed exercise dose. Participants were asked to submit the dose of exercise they completed (i.e. duration for endurance and repetitions for resistance) and rated their breathlessness or rate of perceived exertion on the modified Borg scale [87]. Submitting an exercise would show a 'tick' in the box next to the exercise so participants could monitor which exercises they completed. Exercise session circles would incrementally fill in with colour as participants complete exercises and turn green once all exercises in session completed. This allowed participants to monitor how much of the exercise program they had completed. See Appendix 7 for further detail of the exercise protocol.</p>
Symptom monitoring questionnaires	<p><u>Daily:</u> Participants were instructed to record their daily symptoms (i.e. breathlessness, cough, sputum colour, sputum volume, wheeze, fever [yes/no], exacerbation [yes/no]) on the m-PR™ app. Participant could monitor their symptoms as a score or as a graph. Circles next to the questionnaire title on the 'home page' would turn green when participants completed the questionnaire.</p> <p><u>CAT:</u> Participants were instructed to complete a CAT questionnaire once a week. The questionnaire title would disappear from the 'home page' once participant had completed it and would reappear the following week.</p> <p><u>mMRC:</u> Participants were instructed to complete a mMRC dyspnoea scale once a week. The questionnaire title would disappear from the 'home page' once participant had completed it and would reappear the following week.</p>
Educational videos	<p>Participants received two to four educational videos each week that would appear in their 'rehabilitation program' section. Participants could also view all educational videos in the 'Menu' during any week of the program. Participants could watch the videos as many times as they wished. A circle would incrementally fill with colour as participants watched the videos and turn green once they had watched the video until the end. This allowed participants to monitor which videos they had watched. See Appendix 6 for list of educational videos.</p>

Exercise videos	Exercise videos were informational and included instructions on how to perform the exercise and information on how to exercise safely. Exercises appeared on the same page where participants viewed the prescribed exercise dose and also appeared in the 'Menu'.
Inhaler videos	Participants were asked to watch instructional inhaler technique videos that were based off participant's prescribed medication. These appeared in the 'rehabilitation program' alongside the educational videos during weeks 2 and 3 or were available at all times during the 'Menu'.
Daily goal setting (e.g. step count)	Participants could submit daily step count into m-PR™ app and monitor daily step count entries as a list or as a graph with the step count goal appearing on both. Refer to Appendix 7 for physical activity intervention protocol.
Electronic COPD medication action plan	If a participant had a COPD medication action plan prescribed by their medical practitioner, the information was uploaded to the m-PR™ app and participants could view this at any time.
In-app notifications	Participants could view in-app notifications by pressing on the 'envelope' button on the 'home screen' (i.e. these were not 'pop-up' notifications). A minimum of three standard notifications were sent each week and were designed to educate, motivate and support participants. Additional notifications were sent when participant had outstanding tasks for that week.
Menu	The 'menu' included information on how to use the m-PR™ app; a safety guide for exercising at home and what to do in the event of abnormal symptoms during exercise; breathlessness and rate of perceived effort scale; stretching exercises; view all submitted app data including symptoms, exercises and daily goals; watch education, exercise or inhaler videos, and; links to external websites that were customised for the participant
Clinician web-portal	Healthcare professional could view participant's submitted data; view alerts if participants symptoms change significantly (based off computer algorithm); view which videos participant had watched; prescribe exercise type, frequency and dose each week; and prescribe daily step goal each week. A detailed log of all participant interactions with the m-PR™ app could be exported as a spreadsheet.

Components of the m-PR™ app. App: application; CAT: COPD Assessment Test; COPD: chronic obstructive pulmonary disease; mMRC: modified Medical Research Council Dyspnoea scale; m-PR: mobile pulmonary rehabilitation.

Appendix 6. Educational and inhaler videos and week.

	Video/Audio Title	Week occurs in m-PR program
1	Introduction to pulmonary rehabilitation and m-PR	Week 1
2	Relaxation - progressive muscle relaxation	Weeks 1,5 and 8
3	Breathlessness management techniques	Week 2
4	How do your lungs work?	Week 2
5	Mindfulness of breath (audio)	Weeks 2 and 6
6	Understanding your lung disease and breathlessness	Week 3
7	Airway clearance techniques	Week 3
8	Smoking cessation	Week 3*
9	Knowing your medications and action plans	Week 4
10	Patient experience video	Week 4
11	Managing your lung disease	Week 4
12	Mindfulness - body scan	Weeks 4 and 7
13	Managing fatigue	Week 5
14	Nutrition – general healthy eating	Week 6
15	Nutrition – healthy eating and weight gain	Week 6*
16	Nutrition – healthy eating and weight loss	Week 6*
17	Anxiety and depression and coping strategies	Week 7
18	Supportive care and end of life issues	Week 8
19	Inhaler demonstration video (personalised to each participant)	Weeks 2 and 3

*video uploaded to m-PR program only if appropriate for the participant.

m-PR: mobile pulmonary rehabilitation application.

Appendix 7. Consensus on Exercise Reporting Template (CERT).

Item	Item Detail	Study Protocols	
		m-PR group	Centre-based PR group
WHAT: materials			
1	Detailed description of the type of exercise equipment (e.g. weights, exercise equipment such as machines, treadmill, bicycle ergometer, etc.)	<p><u>Endurance exercise:</u> Ground-based walking required no equipment. Equipment was used if available to the participant and appropriate (e.g. treadmill or stationary cycle).</p> <p>Nine (24%) participants had access to a treadmill and eight (21%) had access to a stationary cycle. 36 (95%) participants were prescribed ground-based walking as part of their program.</p> <p><u>Resistance exercise:</u> A chair and steps were used for lower limb functional exercises if the participant had access to these. For upper limb functional exercises, household items (e.g. bags/cans of food or water bottles) were used or free hand weights if the participant had access to these and if appropriate.</p> <p><u>Physical activity:</u> A FitBit Inspire activity tracker (wrist-worn), or the participant's own wrist-worn activity tracker, was used to measure daily step count.</p>	<p><u>Endurance exercise:</u> A treadmill, stationary cycle, indoor gym walking track or combination thereof was used.</p> <p>39 (93%) participants and 41 (98%) participants were prescribed exercises on the treadmill and stationary cycle respectively. Seven (17%) participants were prescribed ground-based walking for at least one centre-based session. All participants were prescribed ground-based walking for their unsupervised home-based exercise session.</p> <p><u>Resistance exercise:</u> free hand weights ranging from 0.5kg to 5kg, a standard height chair and exercise steps were used.</p>
WHO: provider			
2	Detailed description of the qualifications, teaching/supervising expertise, and/or training undertaken by the exercise instructor	One senior physiotherapist (main author), with over eight years of experience in the field of respiratory physiotherapy, provided the intervention through an initial home-visit and subsequent weekly telephone calls. The study exercise protocol was taught to the physiotherapist by a specialist pulmonary rehabilitation physiotherapist who was an investigator on the trial.	Two senior physiotherapists were present for the centre-based sessions at each site. All physiotherapists were previously trained and worked regularly in a pulmonary rehabilitation program. The study exercise protocol was taught to the physiotherapists by a specialist pulmonary rehabilitation physiotherapist who was an investigator on the trial.
HOW: delivery			
3	Describe whether exercises are performed individually or in a group	Participants had the option to perform exercises individually or with a friend or family member/s.	Participants completed exercises in a group session of up to 10 people.
4	Describe whether exercises are supervised	Exercises were delivered through the m-PR™ app where participants could view the exercise type (supported by	Participants were instructed on what type of exercise to complete and at what

	or unsupervised and how they are delivered	exercise video or written description), dose (duration or repetitions), and intensity (distance or resistance and modified BORG scale). Participants completed their exercises independently and without direct supervision.	intensity. Participants completed their exercises in a gym setting and were directly supervised by the physiotherapists.
5	Detailed description of how adherence to exercise is measured and reported	Participants submitted which exercise they had completed, including the dose (duration or repetitions) and intensity (modified BORG scale) for each exercise, into the m-PR™ app. For physical activity, participants submitted their daily step count into the app every day. All submitted data was automatically synchronised to the clinician web-portal where the physiotherapist could monitor adherence in real-time. Participants were considered adherent if they attempted >70% of the exercise sessions.	Physiotherapists completed a hard copy exercise log specifying the type, dose (duration or repetitions) and intensity (modified BORG scale) that was prescribed and completed by the participant for each session. Participants were considered adherent if they attempted >70% of the sessions. Participants were given a hard copy exercise diary for their home-based exercise sessions (one session each week). Participants would write in the exercise diary which exercise they had completed and on which day. Physiotherapists would verbally ask participants if they had completed their home-based exercise program each week. The exercise diary was collected by a physiotherapist at the end of their program. Adherence to the home-based exercise session was not included in overall adherence results.
6	Detailed description of motivation strategies	Health coaching was provided to participants through regular (3 or more each week) notifications via the m-PR™ app and through weekly telephone calls with a physiotherapist. The participant was able to track their progress on the m-PR™ app. Progress graphics were incorporated into the app to encourage participants to complete daily and weekly tasks.	Health coaching was provided to participants during their supervised exercise sessions. They were also provided with a hardcopy exercise diary to help them track their progress and to encourage them to complete a third session, unsupervised, at home each week.
7a	Detailed description of the decision rule(s) for	<u>Exercises:</u> Endurance and resistance exercises were progressed if participants successfully completed 3	Endurance and resistance exercises were progressed

	<p>determining exercise progression</p> <p>sessions consecutively at the prescribed dose (i.e. duration for endurance and repetitions for resistance).</p> <p><u>Physical activity:</u> Step goals were progressed during weekly phone calls if the participant achieved an average daily step count (using at least 4 days of step count data from the previous 7 days) that was the same or greater than the step goal that was set the previous week. If participants did not achieve the goal, the goal from the previous week was kept the same. If they did not achieve the step goal 3 weeks in a row, the step goal was reduced.</p>	<p>if participants successfully completed 2 sessions consecutively at the prescribed dose (i.e. duration for endurance and repetitions for resistance).</p>
<p>7b Detailed description of how the exercise program was progressed</p>	<p><u>Endurance exercise:</u> Initial exercise duration was prescribed at 20 minutes (excluding rests) based on the participant's baseline 6MWT with intensity commencing at 80% of the average speed achieved during the 6MWT for ground-based walking or treadmill training and 60% of the peak work rate estimated from the 6MWT for cycle training. Duration was increased first by 5 minutes, up to a maximum of 40 minutes. Intensity was increased once 40 minutes of endurance exercise were achieved and was based on using the modified BORG and RPE scales, with the aim of a "moderate" to "somewhat severe" level of exertion or breathlessness (whichever is greater) being achieved during training.</p> <p><u>Resistance exercise:</u> Lower limb functional exercises began at 2 sets of 10 repetitions. Exercises were progressed with an additional 1 set of 10 repetitions to a maximum of 3 sets of 10 repetitions. Hand weights (or household items) were added in 1kg (e.g. 500g in each hand initially) increments once 3 sets of 10 repetitions were achieved. Upper limb functional exercises began at 1 set of 10 repetitions with items in each hand weighing 500g. Exercises progressed by an additional 1 set of 10 repetitions until 3 sets of 10 repetitions were completed. Weights increased by 500g increments once 3 sets of 10 repetitions were achieved. Intensity was based on using the modified BORG and RPE scales with the aim of "moderate" to "somewhat severe"</p>	<p><u>Endurance exercise:</u> Initial exercise duration was prescribed at 20 minutes (excluding rests) based on the participant's baseline 6MWT with intensity commencing at 80% of the average speed achieved during the 6MWT for ground-based walking or treadmill training and 60% of the peak work rate estimated from the 6MWT for cycle training. Duration was increased first by 5 minutes, up to a maximum of 40 minutes. Intensity was increased once 40 minutes of endurance exercise were achieved and was based on using the modified BORG and RPE scales, with the aim of a "moderate" to "somewhat severe" level of exertion or breathlessness (whichever is greater) being achieved during training.</p> <p><u>Resistance exercise:</u> Lower limb functional exercises began at 2 sets of 10 repetitions. Exercises were progressed with an additional 1 set of 10 repetitions to a maximum of 3 sets of 10 repetitions. Hand weights were added in 1kg (e.g. 500g in each hand initially) increments once 3 sets of 10 repetitions were achieved.</p>

	<p>levels of dyspnoea or exertion (whichever is the highest) being achieved during training</p> <p><u>Physical activity:</u> participants were asked to enter their daily steps into the m-PR™ app for one week. A daily step count average was calculated from this first week. An overall goal was set at 30% increase from this daily average. The goal for the first week was set at 5% more than their daily step count average. If the participant achieved the step goal the following week, a new daily step count average was calculated and a step goal of 5% more than their new average was used. If participants achieved a daily step count average of 10,000 steps, their step goal would be to maintain it at this level.</p>	<p>Upper limb functional exercises began at 1 set of 10 repetitions with items in each hand weighing 500g. Exercises progressed by an additional 1 set of 10 repetitions until 3 sets of 10 repetitions were completed. Weights increased by 500g increments once 3 sets of 10 repetitions were achieved. Intensity was based on using the modified BORG and RPE scales with the aim of “moderate” to “somewhat severe” level of dyspnoea or exertion (whichever is the highest) being achieved during training</p>	
8	<p>Detailed description of each exercise to enable replication (e.g. photographs, illustrations, video, etc.)</p>	<p><u>Endurance exercise:</u> ground-based walking was prescribed unless participants had access to and requested to use equipment (e.g. treadmill, stationary bike).</p> <p><u>Resistance exercise:</u> Lower limb functional exercises included sit-to-stand and step-up exercises. If these exercises were not suitable for the participant, they would be prescribed other lower limb exercises such as bilateral standing calf raises, standing hip abduction or leg extension with an ankle weight. Upper limb functional exercises included bicep curls, forward punches, shoulder press, side lateral raise and standing rows. If certain exercises were not appropriate for the participant, the exercise would be substituted with wall push ups or tricep extensions.</p>	<p><u>Endurance exercise:</u> treadmill-based walking or stationary cycling were prescribed. If participants were unable to use one or both exercise machines, indoor ground-based walking was prescribed.</p> <p><u>Resistance exercise:</u> Lower limb functional exercises included sit-to-stand and step-up exercises. If these exercises were not suitable for the participant, they would be prescribed other lower limb exercises such as bilateral standing calf raises, standing hip abduction or leg extension with an ankle weight. Upper limb functional exercises included bicep curls, forward punches, shoulder press, side lateral raise and standing rows. If certain exercises were not appropriate for the participant, the exercise would be substituted with wall push ups or tricep extensions.</p>
9	<p>Detailed description of any home program</p>	<p>All exercises as described above were completed as a home program (i.e. not</p>	<p>Participants were encouraged to complete</p>

	<p>in a supervised gym-based setting). Participants could access educational information (video and written information) on the m-PR™ app that educated and instructed the participant on how to perform each exercise and stretching exercises.</p>	<p>one unsupervised session at home (i.e. not in a supervised gym-based setting) each week. They were provided with a hard copy exercise booklet that described the exercises. The prescription of the home exercises was the same as what the participant completed during their most recent supervised exercise session.</p>
<p>10 Describe whether there are any non-exercise components (e.g. education, cognitive behavioural therapy, massage, etc.)</p>	<p>The m-PR™ app also included informational videos, daily goal setting, symptom monitoring questionnaires, electronic COPD medication action plan (if available), automatic in-app notifications and other written educational informational. Participants were referred as necessary to members of the multi-disciplinary team for assessment and treatment and included an Occupational Therapist, Dietitian, Clinical Psychologist and a Clinical Nurse Consultant. Refer to Table 1 in the previously published protocol paper for further detail on the m-PR™ app and PR program [237].</p> <p>Weekly, semi-structured health coaching telephone calls were conducted and could include: reviewing the participant's exercise program from the previous week and discussing changes to the exercise program for the following week; discussing symptoms and providing education on symptom and disease management strategies; discussing video content; discussing strategies to improve adherence to the exercise program or other app components; providing feedback on progress; and, reviewing physical activity goals (if applicable) and discussing changes to daily step goals for the following week.</p>	<p>Self-management education was offered as needed during supervised, group-based sessions and included topics such as management of exacerbations, use of COPD medication action plans, understanding medications and benefits of ongoing exercise.</p> <p>Participants were offered, when available, to attend weekly group-based face-to-face education sessions with a physiotherapist or another member of the multidisciplinary team. Health care professionals delivering the education sessions had expertise in the education topic. Face-to-face education sessions were not available to all participants throughout the trial period due to the impact of COVID-19 pandemic restrictions.</p> <p>Participants were referred as necessary to members of the multi-disciplinary team for assessment and treatment and included an Occupational Therapist, Dietitian, Clinical Psychologist and a Clinical Nurse Consultant.</p>

WHERE: location			
12	Describe the setting in which the exercises are performed	<p>A comprehensive baseline assessment was conducted face-to-face at one of the five pulmonary rehabilitation centre-based sites.</p> <p>Participants had the option to choose where to exercise. Example settings include at their home residence and/or in the local community such as a park or shopping centre.</p>	<p>A comprehensive baseline assessment was conducted face-to-face at one of the five pulmonary rehabilitation centre-based sites.</p> <p>Participants completed their exercises at one of five pulmonary rehabilitation sites across Northern Sydney Local Health District (Sydney, NSW, Australia). Sites included exercise gyms in hospital outpatient areas and in community health centres.</p>
WHEN, HOW MUCH: dosage			
13	Detailed description of the exercise intervention including, but not limited to, number of exercise repetitions/sets/sessions, session duration, intervention/program duration, etc.	<p>Participants completed three exercise sessions over eight weeks (total of 24 sessions).</p> <p>Participants were given the option to work towards daily step goals which typically started in week 2 or 3 of their program.</p> <p>Exercise dosage and progression is detailed under item 7b.</p>	<p>Participants completed two supervised exercise sessions over eight weeks (total of 16 sessions) and were encouraged to complete one unsupervised session a week (8 sessions).</p> <p>Exercise dosage and progression is detailed under item 7b.</p>
TAILORING: what, how			
14a	Describe whether the exercises are generic (one size fits all) or tailored whether tailored to the individual	<p>Exercise and step goal prescription and progression followed the above-mentioned protocol but was tailored to the individual participant depending on comorbidities (e.g. chronic musculoskeletal pain) and response to exercise.</p>	<p>Exercise prescription and progression followed the above-mentioned protocol but was tailored to the individual participant depending on comorbidities (e.g. chronic musculoskeletal pain) and response to exercise.</p>
14b	Detailed description of how exercises are tailored to the individual	<p>Endurance exercise prescription was based on the participant's baseline 6MWT with intensity commencing at 80% of the average speed achieved during the 6MWT for ground-based walking or treadmill training and 60% of the peak work rate estimated from the 6MWT for cycle training.</p> <p>Endurance and resistance exercise intensity was progressed/regressed to achieve a "moderate" to "somewhat-severe" level of dyspnoea or effort on the modified BORG or RPE scales, respectively.</p>	<p>Endurance exercise prescription was based on the participant's baseline 6MWT with intensity commencing at 80% of the average speed achieved during the 6MWT for ground-based walking or treadmill training and 60% of the peak work rate estimated from the 6MWT for cycle training.</p> <p>Endurance and resistance exercise intensity was</p>

		<p>Exercise type was changed based on what was suitable for the individual participant in terms of comorbidities (e.g. chronic musculoskeletal pain).</p> <p>Participants were given the option to work towards daily step goals. Physical activity goals were set based off the participant's daily step average achieved during the week prior.</p>	<p>progressed/regressed to achieve a “moderate” to “somewhat-severe” level of dyspnoea or effort on the modified BORG or RPE scales, respectively.</p> <p>Exercise type was changed based on what was suitable for the individual participant in terms of comorbidities (e.g. chronic musculoskeletal pain).</p>
15	Describe the decision rule for determining the starting level at which people commence an exercise program (such as beginner, intermediate, advanced, etc.)	Refer to section 7b and 14b.	Refer to section 7b and 14b.
HOW WELL: planned, actual			
16a	Describe how adherence or fidelity to the exercise intervention is assessed/measured	<p>Participants submitted a response through the m-PR™ app to confirm that they had completed an exercise and at what dose and intensity. They would also submit their daily step count into the app. All participant interactions with the m-PR™ app were automatically synchronised to the clinical web-portal where the physiotherapist monitored participant adherence in real-time. Participants were considered adherent to the exercises if they attempted at least 70% of the total prescribed exercise sessions. Participants were considered adherent to the daily step goals if they attempted at least 70% of the days.</p>	<p>Participant adherence to exercise type, dose and intensity was recorded by physiotherapists during their supervised exercise sessions. Participants would document which exercises they completed during the unsupervised home session in a hardcopy exercise diary.</p>
16b	Describe the extent to which the intervention was delivered as planned	Refer to Table 5 for adherence results.	Refer to Table 5 for adherence results.

Appendix 8. Baseline characteristics for intention-to-treat, per-protocol and dropout participants.

Characteristics	m-PR			CB-PR		
	Completers	Per-protocol	Dropout	Completers	Per-protocol	Dropout
Participants, n	38	32	6	42	36	4
Age, years	75 (7)	76 (7)	77 (9)	75 (7)	75 (6)	74 (5)
Sex, female, n (%)	19 (50)	17 (53)	2 (33)	23 (55)	19 (53)	4 (100)
Height, m	1.7 (0.1)	1.7 (0.1)	1.7 (0.1)	1.7 (0.1)	1.7 (0.1)	1.6 (0.04)
Weight, kg	79 (16)	79 (17)	74 (21)	75 (20)	76 (19)	61 (12)
BMI, kg/m ²	28 (5)	28 (5)	26 (6)	26 (6)	27 (6)	24 (5)
Preferred language, English, n (%)	37 (97)	31 (97)	5 (83)*	41 (98)	35 (97)	4 (100)
Smoking status, n (%)						
Non-smoker	5 (13)	5 (16)	0 (0)	2 (5)	2 (6)	0 (0)
Current smoker	6 (16)	5 (16)	1 (17)	10 (24)	10 (28)	1 (25)
Ex-smoker	27 (71)	22 (69)	5 (83)	30 (71)	24 (67)	3 (75)
Smoking history, pack-years [†]	32 (29)	34 (31)	28 (16)	37 (23)	39 (24)	26 (13)
Employment status, n (%)						
Employed	5 (13)	2 (6)	1 (17)	2 (5)	1 (3)	1 (25)
Not working	33 (87)	30 (94)	5 (83)	40 (95)	35 (97)	3 (75)
LTOT, n (%)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	1 (25)*
Pulmonary function						
FEV ₁ L	1.5 (0.5)	1.5 (0.5)	1.3 (0.5)	1.4 (0.5)	1.3 (0.5)	1.0 (0.4)
FEV ₁ % predicted	59 (14)	60 (14)	56 (19)	56 (13)	54 (13)	54 (19)
FVC L	2.9 (0.9)	2.8 (0.9)	2.9 (0.8)	2.8 (1.0)	2.7 (0.9)	2.0 (0.5)
FVC % predicted	87 (18)	87 (19)	75 (25)	85 (19)	83 (19)	82 (22)
FEV ₁ /FVC %	52 (10)	53 (10)	45 (11)	51 (10)	50 (10)	51 (16)
Severity of COPD, n (%)						
GOLD I	1 (3)	1 (3)	0 (0)	0 (0)	0 (0)	0 (0)
GOLD II	25 (66)	22 (69)	4 (67)	28 (67)	22 (61)	3 (75)
GOLD III	11 (29)	8 (25)	1 (17)	14 (33)	14 (39)	0 (0)
GOLD IV	1 (3)	1 (3)	1 (17)	0 (0)	0 (0)	1 (25)
Comorbidities, n (%) [‡]						
Presence of any comorbidity	38 (100)	32 (100)	6 (100)	42 (100)	36 (100)	4 (100)

Cardiovascular	30 (79)	25 (78)	5 (83)	31 (74)	27 (75)	2 (50)
Cancer	14 (37)	12 (38)	0 (0)	21 (50)	17 (47)	0 (0)
Metabolic	13 (34)	10 (31)	2 (33)	16 (38)	14 (39)	1 (25)
Musculoskeletal	18 (47)	16 (50)	4 (67)	28 (67)	25 (69)	3 (75)
Respiratory	12 (32)	10 (31)	1 (17)	15 (36)	13 (36)	1 (25)
Mental	6 (16)	5 (16)	0 (0)	11 (26)	10 (28)	1 (25)
Other	27 (71)	25 (78)	4 (67)	30 (71)	24 (67)	2 (50)
Respiratory Medications, n (%) [†]						
Short-acting bronchodilator	27 (71)	24 (75)	1 (17)*	23 (55)	23 (64)	4 (100)
Long-acting bronchodilator	11 (29)	8 (25) [#]	3 (50)	20 (48)	20 (56)	3 (75)
Inhaled corticosteroid	5 (13)	4 (13)	0 (0)	2 (5)	2 (6)	2 (50)*
Combination therapy	28 (74)	23 (72)	4 (67)	30 (71)	24 (67)	2 (50)
Oral antibiotics	0 (0)	0 (0)	0 (0)	2 (5)	2 (6)	0 (0)
Oral corticosteroids	2 (5)	2 (6)	1 (17)	3 (7)	3 (8)	0 (0)
Technology skills (adequate or better), n (%) [§]	34 (89)	28 (88)	5 (100)	38 (90)	32 (89)	3 (100)

Values are presented as mean (SD) unless otherwise stated.

Per-protocol analysis excluded participants who were not adherent to the exercise sessions (m-PR = 6, CB-PR = 6).

Technology skills were assessed through a custom-designed questionnaire where participants rated their overall technology skills on a 5-point Likert scale from 'Very Poor' to 'Very Good'.

[†]Smoking history available for n = 83 (m-PR = 39 [ITT = 33, drop out = 6] [per-protocol = 27], CB-PR n = 44 [ITT = 40, drop out = 4] [per-protocol = 34]).

[#]Multiple responses possible.

[§]Missing technology skills data n = 2 (m-PR dropout n = 1, CB-PR dropout n = 1).

*Statistically significant between drop out and ITT within m-PR or CB-PR group.

[#]Statistically significant difference between per-protocol m-PR and CB-PR groups.

BMI: body mass index; CB-PR: centre-based pulmonary rehabilitation group; FEV₁: forced expiratory volume in 1 s; FEV₁/FVC: FEV₁ as a percentage of FVC; FVC: forced vital capacity; GOLD: Global Initiative for Chronic Obstructive Lung Disease; ITT: intention-to-treat; LTOT: long term oxygen therapy; m-PR: mobile pulmonary rehabilitation group.