Research Topics

Walking, cycling and active travel as part of physical activity and public health systems

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Published in
Frontiers in Sports and Active Living
Frontiers in Public Health

ISSN 1664-8714
ISBN 978-2-8325-4763-2
DOI 10.3389/978-2-8325-4763-2

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Walking, cycling and active travel as part of physical activity and public health systems

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Citation
Kelly, P., Gill, J. M. R., Bourne, J., Richards, J., Salvo, D., eds. (2024). *Walking, cycling and active travel as part of physical activity and public health systems*.
Lausanne: Frontiers Media SA. doi: 10.3389/978-2-8325-4763-2

Table of contents

frontiers | Frontiers in Sports and Active Living

TYPE Editorial
PUBLISHED 01 November 2023
DOI 10.3389/fspor.2023.1321450

OPEN ACCESS

EDITED AND REVIEWED BY
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RECEIVED 14 October 2023
ACCEPTED 19 October 2023
PUBLISHED 01 November 2023

CITATION
Kelly P, Bourne J, Richards J, Salvo D and Gill JMR (2023) Editorial: Walking, cycling and active travel as part of physical activity and public health systems.
Front. Sports Act. Living 5:1321450.
doi: 10.3389/fspor.2023.1321450

Editorial: Walking, cycling and active travel as part of physical activity and public health systems

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KEYWORDS

walking, cycling, health, active travel, public health

Editorial on the Research Topic
Walking, cycling and active travel as part of physical activity and public health systems

Introduction

Increasing active travel is seen as a priority in many parts of the world, as it can facilitate mobility (e.g., reduced congestion), benefit the environment (e.g., reduced pollution and carbon emissions) and improve physical and mental health (1–3). The present Research Topic includes papers on several of the factors which we need to address to increase active travel.

Establishing the benefits and known barriers

In a comprehensive review of the evidence, Logan et al. report the health benefits of cycling, the economic benefits, known barriers, and a summary of approaches to try and promote cycling. This can help make the case for cycling, support advocacy, and inform intervention development. Meanwhile, Kardan et al. reviewed the evidence related to cycling focussing on older adults, highlighting the importance of traffic safety in the evidence base.

In a study that focussed on health, Ding et al. reported positive associations with both physical and mental health and cycling to school in Chinese adolescents. In their multi-country study, Cordovil et al. showed that age of learning to cycle (necessary first step to getting people to cycle more) varies between countries and is likely impacted by individual, environmental, and temporal factors.

Improving our measures

Several studies in this Research Topic investigated ways of measuring active travel, seen as a key step in facilitating behaviour change (4). Malnes et al. reported findings on the convergent validity of a new travel diary for school travel. The role of technology was also explored. Saito et al. assessed the validity and reliability of a smartphone application for measuring walking ability in older adults, while Pesola et al. looked at the ability of a thigh worn accelerometer to assess free-living cycling in children.

The growth of e-cycling

Building on ever improving technology, sales of e-bikes have increased substantially in recent years and e-cycling is becoming increasingly prevalent. In their systematic review, Riiser et al. report evidence of health benefits from e-cycling, particularly increases in cardiorespiratory fitness. However the authors cautioned that the quality of these studies was generally low and more higher quality studies are required to determine the impact of e-cycling on health and the environment to support policy initiatives. Using a qualitative approach, Bourne et al. reported the determinants of e-cycling in people with Type 2 Diabetes. The enjoyment experienced while e-cycling was a key facilitator of engagement. The authors highlight that bike training was important to increase actual and perceived ability to e-cycle. These studies provide important factors for consideration in future e-cycling promotion efforts.

Intervention development

Connell et al. reported the comprehensive development and piloting of a multi-component workplace cycling intervention targeting several identified barriers to cycling reported through engagement with the target population. This type of evidence based, multi-component intervention provides a helpful template for future initiatives to increase the potential for behaviour change.

Policy and partnerships

Niven et al. described learning from 10 years of delivery organisations, academic researchers, and other stakeholders working in partnership on national walking promotion. Power et al. used a systems lens to understand walking policy at a country level. Moving from country to city level, Corr et al. used systems approaches to understand and develop cycling promotion strategies. Collectively these papers demonstrate that although building trusting cross-sectoral relationships can require significant investments of time this multidisciplinary collaboration seems necessary to promote cohesive action. Finally, Kahlmeier et al. described how health economic tools can be used to inform, influence and evaluate active travel intervention and policy. A tool such as the Health Economic Assessment Tool (HEAT) for walking and cycling is appealing to multiple stakeholders including academics, governments and private organisations.

Looking forward

Considering the evidence included in this Research Topic and reflecting on the global impact of the COVID-19 pandemic over the last few years, it appears that we are at a critical juncture in the promotion of active transport. We have seen significant changes in worldwide mobility and travel behaviour. On one side there was a shift towards remote working environments, which reduced overall population commuting with more people working from home. Shifting commuters from motorised to active transport modalities has historically been a key target for walking and cycling initiatives as demonstrated by several studies in this Research Topic. Consequently, we may need to think more broadly about the types of "trips" we target in active transport advocacy.

Conversely, during the pandemic we saw some temporary shifts in the way people interacted with the physical environment immediately around their homes. Many people walked and cycled in their local neighbourhood and discovered local options to be physically active that they were not previously aware of or did not perceive to be safe. This may be something that is still fresh in the minds of the collective population and may have generated a latent demand for intervention, which may present a "once-in-a-generation" opportunity that must be acted upon to encourage lasting change, before it is too late. Several articles in this Research Topic outline how governments and organisations could intervene at the policy and community level to bring about more sustained active transport behaviour change.

Author contributions

PK: Writing – original draft. JB: Writing – review & editing. JR: Writing – review & editing. DS: Writing – review & editing. JG: Writing – original draft, Writing – review & editing.

Funding

The authors declare that no financial support was received for the research, authorship, and/or publication of this article.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The authors declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

Publisher's note

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ORIGINAL RESEARCH
published: 06 April 2022
doi: 10.3389/fspor.2022.761723

Establishing the Convergent Validity of the Travel Habit Questions in the Health Behavior in School-Aged Children Questionnaire by Quantifying Active Travel in Norwegian Adolescents

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OPEN ACCESS

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Specialty section:
This article was submitted to Physical Activity in the Prevention and Management of Disease, a section of the journal Frontiers in Sports and Active Living

Received: *20 August 2021*
Accepted: *23 February 2022*
Published: *06 April 2022*

Citation:
Malnes L, Haugen T, Hansen BH, Kolle E and Berntsen S (2022) Establishing the Convergent Validity of the Travel Habit Questions in the Health Behavior in School-Aged Children Questionnaire by Quantifying Active Travel in Norwegian Adolescents.
Front. Sports Act. Living 4:761723.
doi: 10.3389/fspor.2022.761723

Background: Active travel (cycling or walking to school) can be a substantial part of adolescents' daily physical activity. Research on transport activities primarily relies on self-reported indices of travel mode and travel time. However, many researchers do not report the psychometric properties of their instruments. The Health Behavior in School-aged Children (HBSC) questionnaire is a commonly used instrument, but the items in this questionnaire on travel habits have not yet been validated. The present study was conducted to investigate the convergent validity and agreement between the HBSC items and a travel diary on (1) transport mode to and from school and (2) travel time to school.

Methods: The study sample consisted of 50 participants in the 9th grade (15 ± 0.3 years, 62% girls) from seven Norwegian schools. Outcome variables included transport mode and travel time derived from the HBSC items and a five-day travel diary. Convergent validity was assessed by evaluating Cohen's kappa for travel mode and the correlation coefficient (Spearman Rho) for travel time. Simple agreement calculations between the two measurement methods were also conducted.

Results: The association between the HBSC questionnaire and the diary for travel mode to and from school was $\kappa = 0.63$ ($P < 0.001$) and $\kappa = 0.77$ ($P < 0.001$), respectively. The total agreement between the HBSC questionnaire and the diary for was 78%. However, the agreement was higher for walking (88%) and cycling (91%) than for motorized transport (67%). For travel time, the Spearman correlation coefficient was $\rho = 0.60$ ($P < 0.001$) between the HBSC questionnaire and the diary. The total agreement on travel time was 67%; however, active commuters (86%) seemed to more accurately estimated travel time than motorized commuters (55%).

Conclusion: Although the overall agreement between the HBSC questionnaire and the diary for mode of transport was 78%, the HBSC questionnaire may underestimate the prevalence of motorized transport compared to walking and cycling.

Trial Registration: ClinicalTrials.gov, identifier: NCT03817047.

Keywords: validation, agreement, travel diary, logs, active commuting, travel habits, cycling, walking

INTRODUCTION

Although regular physical activity has health benefits (Warburton et al., 2010), most Europeans do not meet the current international guidelines for physical activity, even at a young age (Steene-Johannessen et al., 2020), and inactivity remains a significant public health challenge (Kohl et al., 2012). Active travel (cycling or walking to and from school) can be an effective way to incorporate physical activity into everyday life (Sahlqvist et al., 2012; Yang et al., 2014), and efforts to facilitate active travel can help address the concern of physical inactivity.

In the last decades, an increasing number of studies have been conducted on active travel among children and adolescents (Chillón et al., 2011; Villa-González et al., 2018). Chillón et al. (2011) reviewed interventions to increase the prevalence of active travel; and found that school-based interventions had a small effect. However, only two of the included studies reported data on the validity of their measurement instruments, leaving uncertainty regarding the accuracy of their findings. Seven years later, Larouche et al. published an updated review, based on a replicated search, and rated most studies to be of poor quality, partly due to the lack of psychometric properties indicating the validity of their measurements (Larouche et al., 2018). Therefore, future studies with valid measures on travel habits are required (Chillón et al., 2011; Lubans et al., 2011; Lu et al., 2014; Larouche et al., 2018).

Research on travel behavior has mostly relied on self-reported indices of measurement (Chillón et al., 2011; Herrador-Colmenero et al., 2014; Larouche et al., 2018). However, many researchers do not report validity data on their questionnaire items and diaries. Herrador-Colmenero et al. (2014) reviewed 158 articles mentioning self-reported measures to assess active travel and found that only eight articles included data on validity. Criterion validity has been defined as "the extent to which a research instrument is related to other instruments that measure the same variables," and convergent validity measures the correlation with similar instruments (Heale and Twycross, 2015). Observation through a camera is one way to identify and validate modes of transport (Kelly et al., 2014; Carlson et al., 2015); it can provide objective data and is therefore thought to be more accurate than self-reported data (Doherty et al., 2013; Kelly et al., 2014; Carlson et al., 2015). However, the use of a camera can increase participant burden and raise ethical concerns regarding the privacy of children and adolescents (Everson et al., 2019). Other researchers have applied parental questionnaires (Evenson et al., 2008; Herrador-Colmenero et al., 2014; Larouche et al., 2017) and self-reported diaries (Petrunoff et al., 2013) to validate questionnaire items on travel habits in young individuals.

The great diversity in self-reported items on active travel (Chillón et al., 2011; Herrador-Colmenero et al., 2014; Lu et al., 2014) can make it difficult to draw comparisons between studies. The Health Behavior in School-aged Children (HBSC) questionnaire contains items to measure active travel (Roberts et al., 2009). It is a widely used instrument to collect data on travel mode and duration (Gropp et al., 2012, 2013; Helmerhorst et al., 2012; Loureiro and Gaspar, 2014; Morgan et al., 2016; Yang et al., 2016; Hollein et al., 2017; Ian et al., 2017; Pavelka et al., 2017). To our knowledge, data on the convergent validity of the transport-related items included in the HBSC questionnaire have not been published.

The present study was conducted to investigate the convergent validity and agreement between the HBSC questionnaire and a travel diary on (1) mode of transport to and from school and (2) travel time to school among students aged 14–15 years.

MATERIALS AND METHODS

Study Design

The present study was a part of the School in Motion (ScIM) project (Solberg et al., 2021), a cluster-randomized controlled multi-center study conducted in the school year 2017/18. Pupils in the 9th grade (14–15 years) from different parts of Norway had previously participated in pre- and mid-data collection phases. The present study comprised participants from the county of Agder at post-test. The participants filled out a five-day travel diary and reported travel habits in a questionnaire during spring 2018.

Study Participants

Overall, 341 participants were invited to participate in the study by filling out a travel diary, in addition to the original test battery in the main project. Of the 341 pupils invited, 57 returned the travel diary with sufficient data on travel mode to and from school ($n = 54$ and 52, respectively) and data on travel time ($n = 49$) to school. Of these, seven participants did not answer the questionnaire, resulting in 50 participants reporting data on travel mode (47 and 46 to and from school, respectively) and travel time ($n = 43$) to school.

Measures

Demographic Variables

Data on age, gender, and ethnicity were self-reported. We also measured the participants' height, weight, and waist circumference.

Travel Diary

A member of the research team handed out the travel diary and explained how to report the data. The reporting started the next day for 5 consecutive weekdays. In the diary, the participants reported whether they traveled by foot, by bicycle, e-bike, by car, collectively or by other. The participants also noted the time they traveled from home to school, arrived at school, traveled from school back home, and arrived home after school. If needed, the participants could also write a comment. The travel diary was distributed between April and June on various dates to avoid holidays and special events at the schools. Opening hours for the schools were between 8 and 9 am, and closing hours varied between 1 and 3 pm, varying between schools and day of the week. The participants registered travel data between 3 and 36 days before answering the questionnaire, except at one school completing 9 days after answering the questionnaire.

The most-reported mode of transport in the diary was considered the participants' typical mode of transportation and included in the analysis. In cases where the typical mode of transport was unclear ($n = 4$), travel mode was set to missing.

For travel time, the median travel time (minutes) of all logged days was defined as the typical travel time and included in the analysis. When traveling to school in the morning, the participants reported departure time (hh:mm) from home and time of arrival to school. We calculated travel time by subtracting the time of arrival to school from the time of departure. Some participants provided an approximate timeframe in their diary; for example, left for school (hh:mm) 08:10-08:15. In these cases, the mid-point (for example, 08:12:30) was used to calculate the travel time.

HBSC Questionnaire Items

We retrieved three questionnaire items from the HBSC questionnaire (Roberts et al., 2009); two measuring modes of transport (to and from school) and one measuring travel time to school. Due to large weather variations in the Nordic countries during a year (Kolle et al., 2009), there is a risk of estimation bias, which we addressed by adding seasonal and monthly specifications (summer and winter half of the year) to the HBSC items. The items measuring modes during the summer season were included in the present study. More specifically, the question states, "On a typical day in the spring/summer (April to September) is the main part of your journey to school made by…?" followed by a question capturing travel mode from school. The participants answered with the following options: by walking, by bicycle, by car/motorcycle/moped, by bus/trains/subway/ferry, or by other. No participants traveled by car from school, and 10 traveled by car to school, according to the diary. Therefore, simple agreement calculations on car and bus were performed separately, but pooled as motorized transport when presenting results, for ease of communication. The participants reported travel time by answering "How much time does it usually take you to get from home to school in the summer?" with one of the following responses: <5, 5–15, 15–30, 31 min to 1 h, and more than 1 h.

TABLE 1 | Characteristics of the sample and the main population.

	Included sample ($N = 50$)	Invited sample ($N = 291$)
Girls, *n* (%)	31 (62)	147 (51)
Immigrant mother or father, *n* (%)	6 (12)	50 (23)
Age years, mean (SD)	15 (0.3)	15 (0.3)
Height cm, mean (SD)	171 (6.8)	170 (8.0)
Weight kg, median (IQR)	59 (11.8)	59 (13.5)
Waist circumference cm, median (IQR)	68 (7.1)	69 (7.5)

Statistical Analyses

The descriptive data are presented as percentage of participants (N), mean (SD), and median (IQR) for categorical, normally distributed, and skewed data, respectively. Differences in demographic data between the included sample and the invited sample were analyzed by the chi-square, independent samples t-test, or Mann-Whitney U-test as appropriate. The convergent validity of the HBSC questionnaire in relation to the travel diary was assessed by Cohens Kappa (κ) on travel mode and Spearman correlation (ρ) on travel time. The percentage agreement between the two instruments was determined by simple calculations. Data were analyzed using Statistical Package Social Sciences, SPSS version 22 (Chicago, Illinois). The significance threshold was set at $p < 0.05$.

RESULTS

Descriptive Statistics

No significant differences were observed between the included sample and the total invited sample (**Table 1**). Most participants typically traveled by motorized transport (48%), followed by walking (27%), and cycling (25%), as illustrated in **Figure 1**. The median (IQR) travel time to school was 15 (15) minutes.

Convergent Validity and Agreement on Travel Mode

The analysis of convergent validity showed a kappa coefficient of $\kappa = 0.63$, $p < 0.001$ and $\kappa = 0.77$, $p < 0.001$ to and from school, respectively. Overall, the agreement between the HBSC questionnaire and the travel diary was 78%. However, after stratification by the typical mode of transport reported in the diary to and from school, motorized transport (67%) had a lower agreement than both walking (88%) and cycling (91%), as illustrated in **Figure 2**. With respect to trip direction, the agreement for motorized transport was higher from school (54 and 81% to and from school, respectively).

Convergent Validity and Agreement on Travel Time

The analysis of convergent validity on travel time showed a Spearman coefficient of $\rho = 0.60$, $p < 0.001$ to school (**Figure 3**). Overall, the findings showed a 67% agreement between median travel time in the

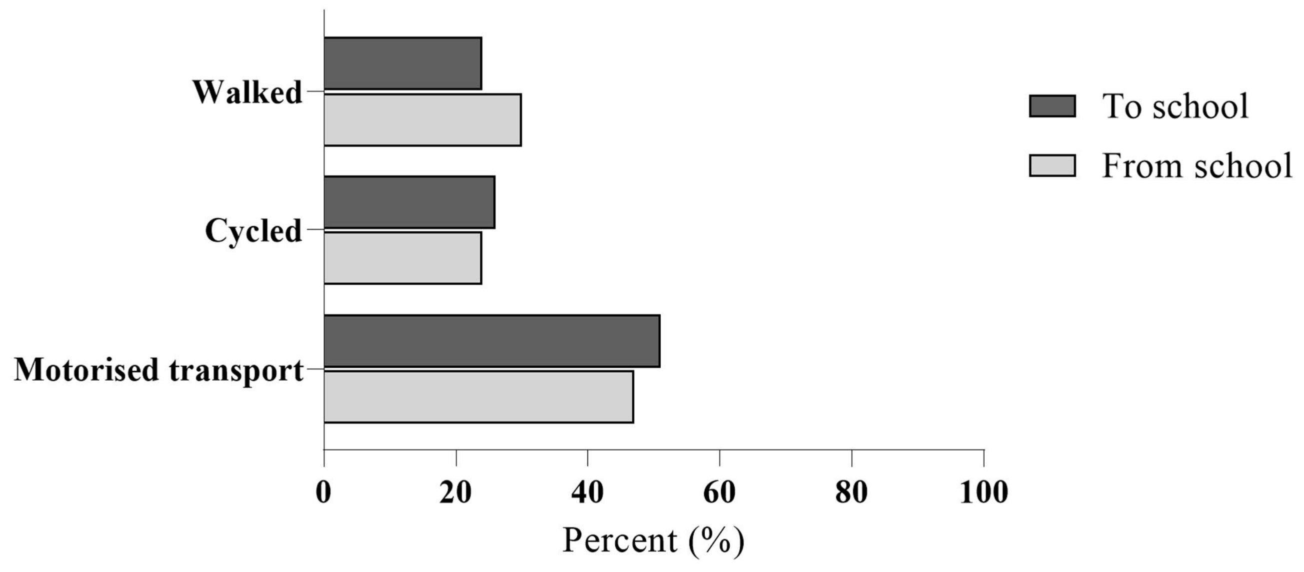

FIGURE 1 | Percentage (%) of participants to ($n = 47$) and from ($n = 46$) school divided by means of transport from travel diaries.

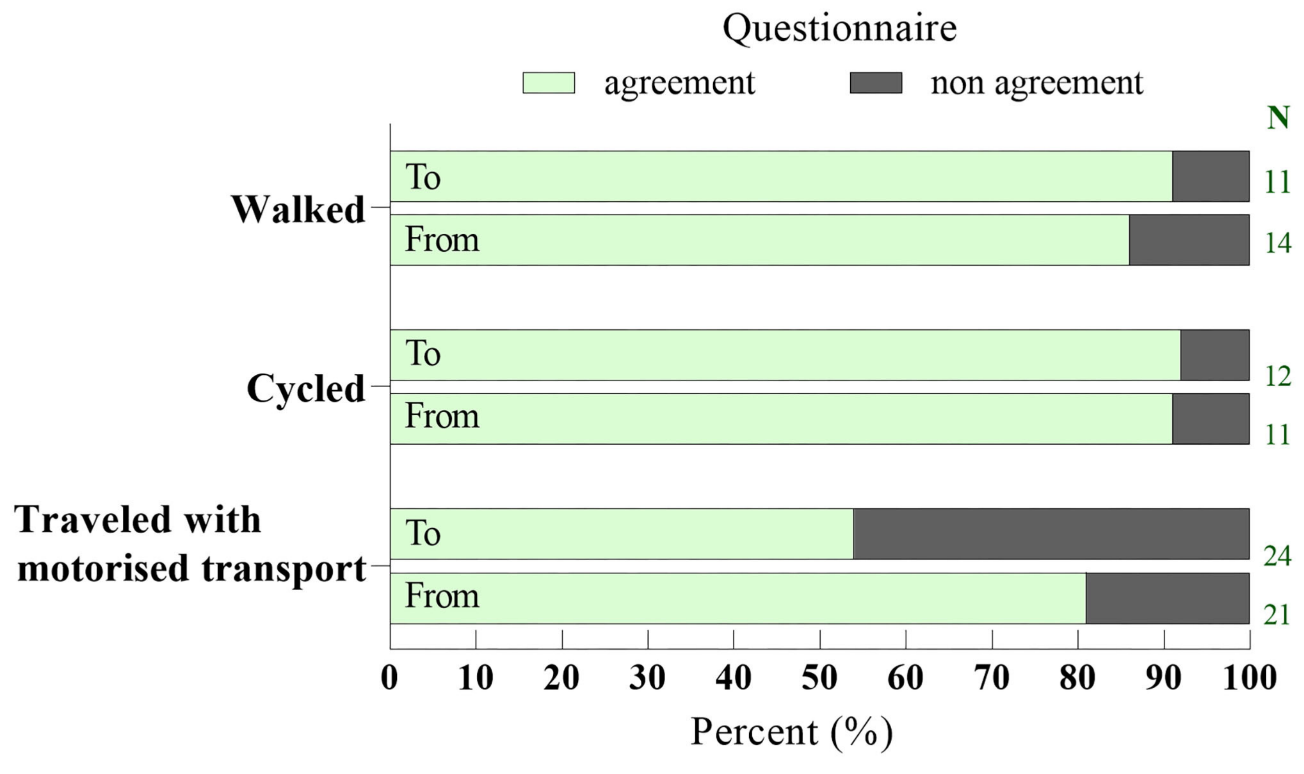

FIGURE 2 | Percentage of reported transport modes to ($n = 47$) and from ($n = 46$) school in the questionnaire, stratified by transport mode from travel diaries.

diary and that reported in the HBSC questionnaire. However, after stratification by the typical travel mode reported in the diary, active commuters had an 86% agreement, while motorized commuters only had a 55% agreement.

DISCUSSION

Overall, most (78%) participants reported the same mode of transport in the HBSC questionnaire and the diary. However, the level of agreement varied by mode of transport as there

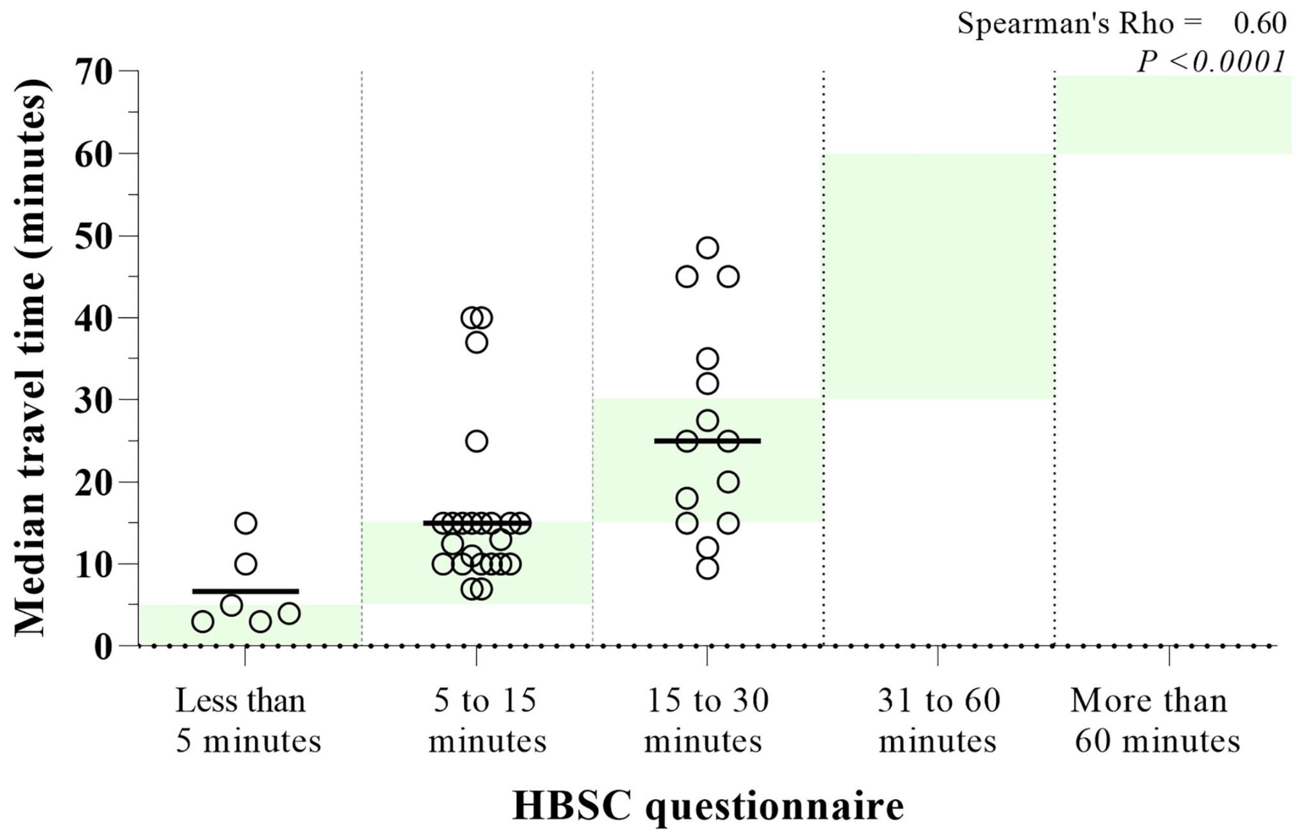

FIGURE 3 | Typical travel duration (median) to school logged in travel diaries (dot) categorized by each participants response from the HBSC questionnaire. Green shadow background indicates the categorize from HBSC in the graph. Vertical line = median in each questionnaire response.

was only 54 and 81% agreement among participants reporting motorized travel mode to and from school, respectively. The remaining participants mainly reported cycling or walking instead. Regarding trip direction, a higher agreement was observed for travel from school, and stratification analysis indicated that this difference was most prevalent among motorized commuters. As mentioned earlier, among motorized commuters no participant was driven from school, as opposed to 10 participants to school, as reported in the diary. Differences in the agreement for trip direction can partly be explained by differences in the use of a car.

With respect to travel time, the overall agreement was 67%, which was lower than that for the mode of transport. Moreover, stratification analysis indicated that active commuters more accurately estimated travel time, since the agreement was higher among participants typically traveling by active modes of transport than motorized modes of transport, as reported in the diary. Furthermore, the participants seemed to underestimate travel time in the questionnaire compared to that in the diary (**Figure 2**), which could be influenced by the lower agreement on travel mode among motorized commuters. According to prior research, it may be more difficult to estimate travel time than the mode of transport. Everson et al. (2019) found higher validity for categorical questions than for items requiring children to estimate time, which they further discussed might be due to the burden of recall.

Our results suggest a kappa coefficient of 0.63 and 0.77 between the HBSC and the diary. Landis and Kock's guidelines define kappa between 0.61 and 0.80 as substantial (Landis and Koch, 1977). However, this classification has been considered arbitrary (Warrens, 2015) and some argue that the cut-off values lack foundation (Vach, 2005).

Petrunoff et al. (2013) conducted a validation study among 45 adults, comparing a diary to an online survey in which the participants answered the following question: "how did you travel for work this week?" Based on a Cohen's kappa of 0.62 when comparing the mode of transport, the instrument was considered to be valid. Their findings were similar to those of the present study. The present study included adolescents and aimed to measure the usual travel mode, whereas Petrunoff et al. included adults and aimed to measure the travel mode during a specific week. Petrunoff et al. found a weaker association for days further back in time than for the most recent days (Petrunoff et al., 2013), which indicates that time between two measurement methods is influenced by recall bias.

Discrepancies between the two measurement methods assessed in the present study may also be explained by social desirability bias (Klesges et al., 2003), as environmentally friendly and physically active modes of transport may be perceived as desirable and may contribute to overreporting of active modes of transport. Another factor that may lead to inconsistencies between the HBSC questionnaire and the diary is estimation bias, particularly if the participants use various travel modes during the school year. The questions "on a typical day is the main part of your journey to school made by…?" and "how much time does it usually take you to get from home to school" were retrieved from the HBSC questionnaire. These questions are broad and depend on the participants' perception of the term "typical" or "usual." Another point to consider is that we ask for a typical mode or travel time, assuming that the participants have one residence, not including separate homes, with two travel routes, as an option. Furthermore, we compared the HBSC questionnaire items measuring usual travel mode with day-to-day reports. The HBSC questionnaire responses may be affected by the participants' intentions; for instance, a participant may have intentions to cycle to school and report it as the usual travel mode, but due to circumstantial factors, motorized transport could have been used.

Strengths and Limitations

We compared the HBSC items to a five-day travel diary. One study strength is the inclusion of a diary as opposed to a parental questionnaire, as questionnaires may be less valid than diaries and logs (Bakker et al., 2020).

We included a mention of time and season as the travel mode during summer may differ from that during winter (Liu et al., 2017), and items aimed to measure travel modes in the summer season were included in the present study. Since we modified the HBSC questionnaire items, the comparability between studies is limited. Moreover, long questionnaires may increase participant burden and the risk of careless responding (Rolstad et al., 2011; Bowling et al., 2020); nevertheless, the items included in the present study appeared early in the questionnaire.

One limitation of the present study is the small sample size caused by the low participation rate (**Table 1**), which may be explained by participant burden, as the participants completed a series of physical tests in the pre-, mid-, and post-data collection phases of the main project.

The HBSC questionnaire asks the participants to report travel mode on a typical day, whereas the diary captures the travel mode during a specific week, assuming that the reported week was typical for every participant. The diary also provides continuous data on travel time, whereas the HBSC questionnaire provides categorical data. Furthermore, there is a lack of temporality between the two estimates of travel mode and time, as the participants answered the HBSC questionnaire items between 3 and 36 days before logging the diary. The lack of agreement might then be attributable to true differences in travel mode/time between the measurement periods. Then again, avoiding holidays and days off at school when distributing the diary would increase the chance of having a typical week, making the diary more comparable to the questionnaire items.

We included Norwegian adolescents in the 9th grade and obtained data for the summer half of the year; hence the findings may not be transferable to other subgroups or seasons. Moreover, the diary has not been previously validated using an objective measure.

This is the first study aiming to validate the HBSC items on active travel and therefore would be relevant for any researchers applying these items as a measurement method. Knowledge about the accuracy of the HBSC questionnaire is essential for researchers and readers. It contributes to a broader understanding of data based on the widely used HBSC items and highlights that the validity may vary among participants traveling with different modes of transport. However, it is uncertain how transferable the findings are to other populations around the world. Differences in climate (Liu et al., 2017), infrastructure and travel habits (Tremblay et al., 2016) can be among factors that limit generalizability to other countries. Nevertheless, our findings can be a supplement to future validation studies and indicate how validity between different populations may vary. Furthermore, more studies are needed on the convergent validity of the HBSC questionnaire items on active travel preferably comparing with observations or objective measures.

CONCLUSION

Although the overall agreement between the HBSC questionnaire and the diary was 78%, the questionnaire may underestimate the prevalence of motorized transport compared to that of active modes of transport.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author, LM, upon reasonable request.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Regional Committees for Medical and Health Research Ethics (REC). However, the need for approval was waived and it was reasoned that our research is not health research. Furthermore, the Norwegian Center for Research Data (project nr.: 49094) assessed the project and concluded that the processing of personal data is regulated by law, §7–27 in the Personal Data Regulations. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

LM, TH, and SB conceptualized the aims of the paper. LM drafted the manuscript, designed the diary, and contributed to the data collection. EK, TH, and SB conceived and designed the study design. BH contributed to the data analysis and interpretation of results. All authors have contributed to drafting and critically revised the work. All authors read and approved the final version of the manuscript.

FUNDING

The Norwegian Directorate for Education and Training funded the main project, the School in Motion study. The present study was a part of a Ph.D. project and funded by the University of Agder.

ACKNOWLEDGMENTS

We would like to thank all participants and parents for providing valuable data material. We would also like to thank the teachers and school leaders for their collaboration and contribution to the data collection phases.

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frontiers | Frontiers in Public Health

ORIGINAL RESEARCH
published: 28 April 2022
doi: 10.3389/fpubh.2022.861390

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Learning to Cycle: A Cross-Cultural and Cross-Generational Comparison

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OPEN ACCESS

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Specialty section:
This article was submitted to Children and Health, a section of the journal Frontiers in Public Health

Received: *24 January 2022*
Accepted: *05 April 2022*
Published: *28 April 2022*

Citation:
Cordovil R, Mercê C, Branco M, Lopes F, Catela D, Hasanen E, Laukkanen A, Tortella P, Fumagalli G, Sá C, Jidovtseff B, Zeuwts L, De Meester A, Bardid F, Fujikawa R, Veldman S, Zlatar S and Estevan I (2022) Learning to Cycle: A Cross-Cultural and Cross-Generational Comparison. Front. Public Health 10:861390. doi: 10.3389/fpubh.2022.861390

Background: Learning to cycle is an important milestone for children, but the popularity of cycling and the environmental factors that promote the development and practice of this foundational movement skill vary among cultures and across time. This present study aimed to investigate if country of residence and the generation in which a person was born influence the age at which people learn to cycle.

Methods: Data were collected through an online survey between November 2019 and December 2020. For this study, a total of 9,589 responses were obtained for adults (self-report) and children (parental report) living in 10 countries (Portugal, Italy, Brazil, Finland, Spain, Belgium, United Kingdom, Mexico, Croatia, and the Netherlands). Participants were grouped according to their year of birth with 20-year periods approximately corresponding to 3 generations: 1960–79 (generation X; $n = 2,214$); 1980–99 (generation Y; $n = 3,994$); 2000–2019 (generation Z; $n = 3,381$).

Results: A two-way ANOVA showed a significant effect of country, $F_{(9,8628)} = 90.17$, $p < 0.001$, $\eta_p^2 = 0.086$, and generation, $F_{(2,8628)} = 47.21$, $p < 0.001$, $\eta_p^2 = 0.122$, on the age at which individuals learn to cycle. Countries with the lowest learning age were the Netherlands, Finland and Belgium and countries with the highest learning age were Brazil and Mexico. Furthermore, the age at which one learns to cycle has decreased across generations. There was also a significant country x generation interaction effect on learning age, $F_{(18,8628)} = 2.90$, $p < 0.001$; however, this effect was negligible ($\eta_p^2 = 0.006$).

Conclusions: These findings support the socio-ecological perspective that learning to cycle is a process affected by both proximal and distal influences, including individual, environment and time.

Keywords: cycling, country, generation, active travel, children

INTRODUCTION

Learning to cycle is an important milestone in childhood that has important implications for future life (1, 2). Across many cultures, the use of bicycles is the first personal active traveling behavior for children to extend their territorial scope, ranging from home to school and other meaningful places (3–6). Being able to cycle extends children's possibilities to actively play outdoors and increases their autonomy, allowing for independent travel at longer distances and higher speeds than walking (7). Cycling is considered to be a foundational movement skill, since it impacts an individual's capability to be physically active and can promote physical activity and health across the lifespan (8). Moreover, cycling is associated with extensive health, economic and environmental benefits (9, 10). In some contemporary cities, as people start valuing sustainability and believing that the car's liabilities outweigh its benefits, the bicycle has emerged as an alternative to the car, mainly for commuting (11, 12). Cycling as a means to actively commute, has several positive health implications such as enhancement of cardiorespiratory fitness (13). Additionally, bicycles are a non-polluting (or low-polluting in the case of electric bicycles), highly energy-efficient mode of active and sustainable transport. As such, cycling can be considered central to different sustainable development goals outlined by the United Nations, including promoting healthy lives and well-being for all and making cities and communities inclusive, safe, resilient and sustainable (14).

Although the benefits of cycling are highly recognized, the popularity of cycling among people, as well as the status of cycling in transport infrastructure and policy, have varied across time and cultures (15–18). This has potentially influenced the importance placed on learning to cycle in different countries across different generations. The influence of time and culture in the process of learning to cycle can be framed by Bronfenbrenner's bioecological theory (19). This theory states that development occurs through an evolving process of reciprocal interactions between the person and multidimensional levels of the environment. Specifically, Bronfenbrenner's Process-Person-Context-Time (PPCT) model can be used to theoretically describe the process of learning to cycle. Learning to cycle can be seen as a proximal process that is dependent on the reciprocal interaction between the person and the environment, which occurs on a fairly regular basis over an extended period of time (19, 20). From this perspective, the individuals who teach the child to cycle as well as the bicycle itself are important elements of the immediate environment with which the child interacts regularly during the learning process.

According to the PPCT model, the process of learning to cycle will also be influenced by the personal characteristics of the child who is learning (e.g., age, skill level or motivation). Each child will learn at a different pace. This individual learning process is also impacted by the child's environment, involving four interrelated systems, from proximal to distal: (a) the microsystem, (b) the mesosystem, (c) the exosystem and (d) the macrosystem. The microsystem refers to the environments where face-to-face interactions occur, such as the child's home, school, or peer group. If people in these microsystems (e.g., parent/caregiver) value cycling and offer the child opportunities to regularly practice cycling, the learning process is enhanced (21). The mesosystem refers to the interactions between different microsystems (e.g., family- and peer relationships). The exosystem refers to the contexts that have an indirect influence on a child's development, even though the child is not an active participant in these contexts (e.g., parents' work context). Finally, the macrosystem refers to the social and cultural context in which the child is immersed, with its set of values and traditions. If, in a given culture, cycling is valued and bicycle-friendly infrastructures (e.g., bike lanes, safe paths) allowing children to cycle safely are available, it is expected that more children will use their bicycles to travel to school or to hang out with friends than when those conditions are not present (22). The final concept of the PPCT model is time. Time is related to the chronosystem, which consists of the socio-historical context the child lives in, as well as the changes that occur over the child's life course. For example, the importance given to cycling and active transportation has changed across different generations (15, 23) as well as the type of bicycles available for learning (15, 24). Even within the same generation, the average age at which children are given their first bicycle could vary and this will influence the learning process (19, 20).

The social, cultural and geographic influence on the development of foundational movement skills is also considered in the lifelong physical activity model proposed by Hulteen et al. (8). The authors suggest that foundational movement skills, such as cycling, should be viewed through a "socio-cultural and geographical" filter. That is, the importance placed on learning certain skills will vary across different cultures and geographic locations (i.e., countries, regions). As such, cycling may be considered a more important foundational skill in countries where cycling is highly valued, compared to countries where a cycling culture is less present (23, 25, 26). For instance, in the Netherlands cycling is frequently used to commute from home to school or work and learning to cycle is an important first step to maintain health-enhancing physical activity habits across the lifespan; however, in other countries (e.g., Brazil), learning how to play soccer is culturally considered as a better way to fulfill that purpose. Learning a foundational movement skill—a result of a simultaneously proximal and distal process—needs to be framed by its cultural geography. That is, where cycling is considered a socially valued travel mode, also enabled by bicycle–friendly urban planning, it can help increase the perceived importance of learning and developing such a foundational skill. As noted by Hulteen et al. (8), these cultural constraints can influence the timing and onset of cycling.

The adoption of Bronfenbrenner's bioecological theory (1995) and Hulteen and colleagues' conceptual model of physical activity across the lifespan (2018) provides a comprehensive approach to understanding the process that enables a child to learn to cycle. In the present study, we focus specifically on studying the influence of the macrosystem and the chronosystem in the learning process. More specifically, an international online survey was created to investigate the association of (1) the country of residence (macrosystem), and (2) the historical time or generation in which a person was born (chronosystem) in the age of learning how to autonomously cycle (with pedals and without training wheels). It was hypothesized that the age of learning how to cycle would differ across geographical locations of residence and generation of birth (8, 20).

METHODS

Survey

The international project L2Cycle (Learning to Cycle) aims to assess different aspects related to the process of learning to cycle in different countries (e.g., learning age, learning paths, type of bicycles used, people involved in the learning process). For this purpose, a survey was created on LimeSurvey and it was hosted at the Faculty of Human Kinetics (University of Lisbon) server. The survey was approved by the Faculty of Human Kinetics ethics committee (process number 22/2019), launched online on November 22, 2019 and publicized through social media (Facebook, Instagram, Twitter and WhatsApp), and by email. In addition, partnerships with cycling federations, children's and parents' magazines and non-profit cycling organizations were established in different countries for dissemination on their websites and in paper magazines. Data for the current study were collected between November 22, 2019 and December 2, 2020.

At a first stage, an initial version of the survey was developed by a group of four experts in child development and was tested online among 485 participants. A sub-sample of 30 participants was additionally asked about the comprehension of the survey. Adjustments were made accordingly (e.g., deleting questions related to age of achieving certain motor milestones, and some questions were reformulated refining questions to improve clarity). At a second stage, the survey was discussed with a group of five international experts who provided further suggestions (e.g., adding questions regarding mother language and different seasons of the year). Finally, the survey was translated into 10 different languages [Portuguese (Portugal and Brazil), English, German, Croatian, Finnish, French, Dutch, Italian, Japanese and Spanish], by experts on motor behavior or motor development, and validated by country specific native speakers.

The final form of the survey took approximately 5 to 15 min to complete (depending on the number of children), could be answered anonymously, and comprised three sections:

1. "About you"-Questions about the participant's own cycle experience and biographical data (e.g., place of residence, age, sex, physical activity habits, if they know how to cycle, if not–why not, if yes-when did they learn how to cycle, what types of bicycles were used and in what sequence, where did they learn, who taught them, how often do they cycle, what do they use it for).

2. "About your oldest child" (to be completed only if the participant has at least one child)-These questions are the same as the questions in the first group but regarding the participant's oldest child.

3. "About your youngest child" (to be completed only if the participant has more than one child)-These questions are the same as the questions in the first group but regarding the participant's youngest child.

Sample

A total of 10,640 responses regarding adults and children (parental responses) living in 29 countries were completed online. For the purpose of this study, only countries with more than 80 responses were considered. This number was based on a sample size calculation performed using the G * Power 3.1.7 Software (Universität Düsseldorf, Germany), considering the analysis of variance (Anova–one way), for a power of 0.8, alpha significance level $\leq$ 0.05, and estimated effect size of 0.25 (minimum difference to be detected = 2.05 and estimated SD = 10). In order to analyze differences in earliest independent cycling age across generations, participants were grouped according to their year of birth considering 20-year periods that roughly correspond to 3 generations: 1960–79 (generation X; n = 2,214; 1980–99 (generation Y, or the millennials; n = 3,994); 2000–2019 (generation Z; n = 3,381). Responses regarding children born in 2020 (too young to be able to ride a bicycle) or adults born before 1960 - a limited number in many countries-were not included in this study. Descriptive data of the participants included in this study is presented in **Table 1**.

Statistical Analysis

Descriptive statistics and frequency analysis were used to characterize the final sample. For the subsequent analysis, a two-way ANOVA was performed to investigate the effects of country of residence (ten countries), generation (three generations), and the interaction between country and generation, on the age at which individuals learned to cycle independently (i.e., riding a traditional bicycle with pedals and without training wheels). Due to non-homogeneity of variances, unequal N HSD *post hoc* tests were used to further investigate significant interaction and main effects. The significance level was set at 0.05.

RESULTS

Learning Age Across Countries

The country of residence significantly influences the age at which one learns how to cycle independently with pedals and without training wheels, $F_{(9,8628)} = 90.17$, $p < 0.001$, $\eta_p^2 = 0.086$. Significant differences were found in learning age among most countries (**Figure 1**). More specifically, our findings show different "learning age-geographical" landscapes.

In the Netherlands and Finland, learning age was significantly lower than in all other countries, except for Belgium (no significant differences). In Belgium, learning age was significantly

TABLE 1 | Sample distribution (*n*), means and standard deviations of age (years), sex distribution (%), and frequency of people who know how to ride a bicycle (%) in the sample of study.

Country	*n*				Age (years)	Sex (%)		Able to cycle (%)	
	Total	Gen X	Gen Y	Gen Z	M (SD)	Female	Male	No	Yes
Portugal	2,386	562	828	996	26.05 (15.36)	57.4	42.6	12.5	87.5
Italy	1,585	370	714	501	27.60 (14.88)	64.7	35.3	9.0	91.0
Brazil	1,455	381	650	424	29.06 (14.91)	64.2	35.8	13.1	86.9
Finland	906	240	367	299	28.82 (16.00)	56.0	44.0	5.0	95.0
Spain	884	153	381	350	25.77 (14.77)	49.4	50.6	9.3	90.7
Belgium	703	240	223	340	24.40 (16.15)	56.8	43.2	7.8	92.2
UK	630	239	265	126	34.17 (15.03)	49.4	50.6	3.5	96.5
Mexico	552	43	318	191	23.69 (8.72)	62.4	37.6	12.1	87.9
Croatia	369	71	180	118	26.31 (14.12)	65.3	34.7	7.0	93.0
Netherlands	119	15	68	36	27.38 (13.01)	68.9	31.1	2.5	97.5
Total	9,589	2,214	3,994	3,381	27.30 (15.07)	58.9	41.1	9.7	90.3

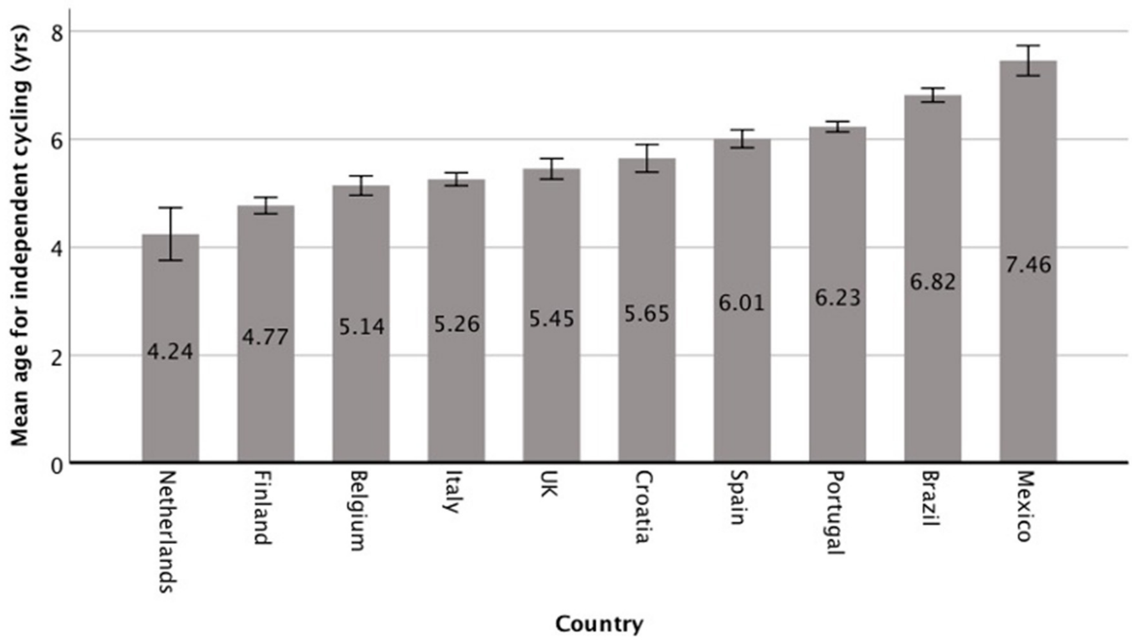

FIGURE 1 | Mean age to learn how to cycle independently by country. Error bars represent 95% CI.

lower than in the other countries, except for the Netherlands, Finland and Italy (no significant differences). In Italy, learning age was significantly higher than in the Netherlands and Finland, and significantly lower than in all other countries; it was not significantly different than in Belgium, UK and Croatia. In the UK, learning age was significantly higher than in the Netherlands, Finland and Belgium, and significantly lower than in Portugal, Brazil and Mexico, but not significantly different than in Italy, Spain and Croatia. In Croatia, learning age was significantly higher than in the Netherlands, Finland and Belgium, and significantly lower than in Brazil and Mexico, but not significantly different than in Italy, UK, Spain and Portugal. In Spain, learning age was significantly higher than in the Netherlands, Finland, Belgium and Italy, and significantly lower than in Brazil and Mexico, but not significantly different than in the UK, Croatia and Portugal. In Portugal learning age was significantly higher than in the Netherlands, Finland, Belgium, Italy and UK, and significantly lower than in Brazil and Mexico, but not significantly different than in Croatia and Spain. In Brazil and Mexico, learning age was significantly higher than in all other countries.

Learning Age Over Generations

There was a significant main effect of generation on the age at which a person learns to cycle, $F_{(2,8,628)} = 47.21$, $p < 0.001$, $\eta_p^2 = 0.122$. As shown in **Figure 2**, the learning age was lower in younger generations. *Post hoc* analysis showed there were significant differences in learning age between all generations. Specifically, Generation X (i.e., born in 1960–79) learned to cycle independently at a later age compared to Generation Y (i.e.,

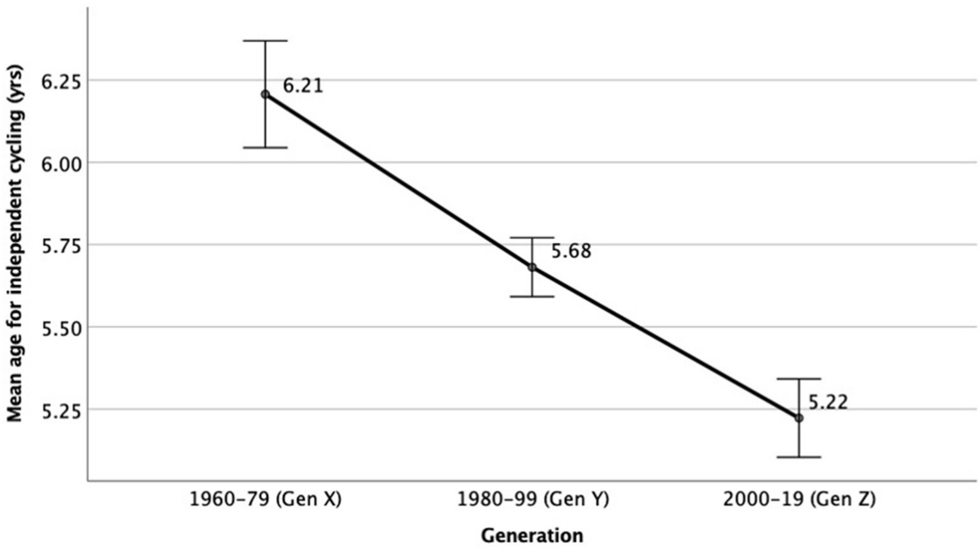

FIGURE 2 | Mean age to learn how to cycle independently by generation. Error bars represent 95% CI.

born in 1980–99) ($p < 0.001$), as did Generation Y compared to Generation Z (i.e., born in 2000-19) ($p < 0.001$).

Learning Age by Generation and Country

There was a significant generation x country interaction effect on learning age, $F_{(18,8,628)} = 2.90$, $p < 0.001$. Generational changes differed slightly among countries with the decline in learning age being less evident in countries in which the learning age has been consistently low across generations (e.g., the Netherlands; see **Figure 3**), but the interaction effect size was negligible ($\eta^2_p = 0.006$). The learning age for independent cycling is generally lower in later generations in all countries, and countries generally maintained their rank relative to the others across time.

DISCUSSION

In the present study we confirmed the hypothesized influence that the macrosystem and the chronosystem have on the age of learning to cycle (20). Results indicated that age to learn how to cycle differs across geographical locations of residence and the generation of birth, as discussed in greater detail in the next sections.

Learning Age in Different Countries

Based on the results of the present study, we can divide the participating countries in three main groups according to the age at which children learn to cycle independently: group 1 (the Netherlands, Finland and Belgium), group 2 (Italy, UK, Croatia, Spain and Portugal), and Group 3 (Brazil and Mexico).

These group differences suggest there are geographical, social, cultural and political aspects underlying the status of active travel and cycling in different countries. These aspects are linked to spatial properties and features within the built environment, which make the places for children to learn how to cycle more or less inviting (27). The groups and the order of the countries within each group in our study also seem to reflect the cycling modal share in each country. European reports and statistics (28, 29) indicate that within Europe, the share of cycling as a travel mode varies between 27.0% in the Netherlands and 0.5% in Portugal. The order of the European countries in the cycling modal share statistics is the same as in our results (except for Croatia for which there was no information on the modal share). The Latin American countries are also known to have low levels of cycling modal share (26, 30). In fact, Goel et al. (26) studied cycling behavior in 17 countries across six continents and concluded that among the studied countries, the Netherlands had the highest level of cycling modal share (26.8%) and Brazil had the lowest (0.8 %) (Mexico was not included in the study). Thus, it seems that in countries with a higher cycling modal share, children tend to learn to cycle earlier than in countries where cycling is less popular.

In group 1 (the Netherlands, Finland and Belgium), measures for active transportation and environmental sustainability seem to be more at the heart of political concerns than in the other two groups, and therefore more embedded within the socio-cultural tissue. Northern European countries seem to be leading initiatives for transition from motorized vehicle transport to active travel, e.g., Finland has set goals to increase cycling and walking by 30% in 2030 (31) and to become carbon neutral by 2035 (32). Conversely, in Southern European or Latin American countries such initiatives are only now starting to emerge, which might explain why children in these countries learn to cycle at a later age.

Among all participating countries in this study, Netherlands, Finland and Belgium have the highest gross domestic product (GDP) per capita (33). This indicates that families in these countries may be more likely to own bicycles, which in turn provides more opportunities for children to learn and practice to cycle. The Global Matrix of Physical Activity Report Cards (34, 35) show that the Netherlands and Finland perform better on active transportation compared to other countries in the present study. In the Netherlands, cycling has been embedded

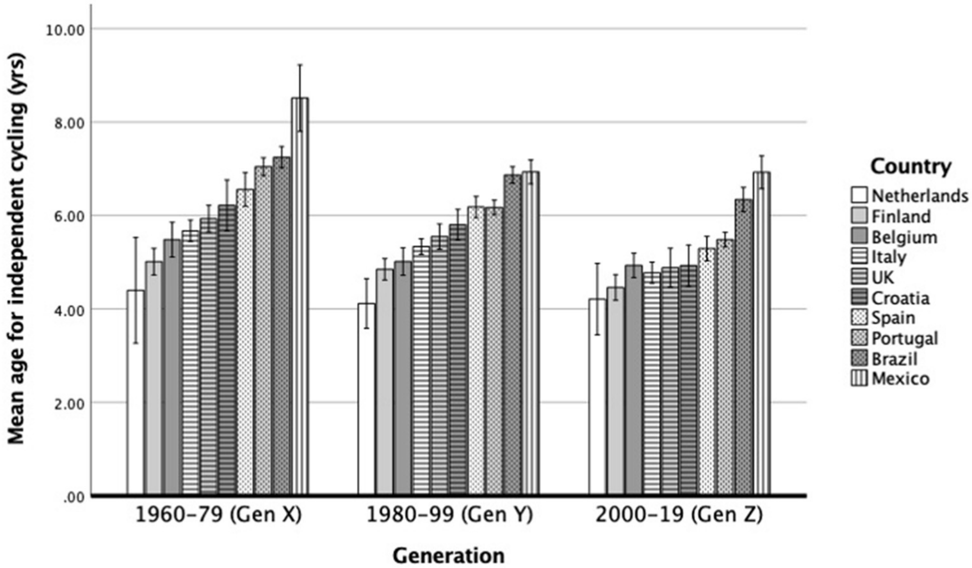

FIGURE 3 | Mean age to learn how to cycle independently by generation and country. Error bars represent 95% CI.

in the culture for over 100 years, having been promoted as a decent and safe mode of transport for 'good civilians' since early 1900 (36). Finland's active transportation among children and youth is ranked as the second highest compared to the other countries in the present study. Active transportation among children is closely linked to children's independent mobility (CIM), which is prominent in Finland (37). Furthermore, CIM and active transportation are both dependent on community and built environment (37), an issue which also separates the Netherlands and Finland from the other countries of the present study. Children and youth living in the Netherlands, Finland, and Belgium share good results regarding the opportunities for active play (34). Active play, especially if performed outdoors, is associated with greater moderate-to-vigorous physical activity and lower sedentary levels (38), thus contributing to the development of a better motor competence (39). It is also worth noting that outdoor play is common in Finnish children's daily life at home and in early childhood education settings (40), and the snowy and icy winter months offer additional stimuli for motor learning.

Belgium is the country with the highest learning age in group 1, presenting non-significant differences with Italy (i.e., the first country in group 2). Belgian respondents on average learned to cycle around the age of five. The current results, therefore, confirm the findings of previous studies regarding the development of cycling skills in Flemish children (i.e., children living in the northern region of Belgium) (41, 42). Belgian children typically master riding a bike when progressing from kindergarten to primary school, although some regional differences exist.

Results found in group 2 (Italy, the UK, Croatia, Spain and Portugal) reflect a lower level of political commitment and investment toward active transportation, environmental sustainability and child-friendly policies among these countries. A clear example related to riding a bike as a cultural and intrinsically integrated aspect of citizen's lives is active transport in urban environments, which is also linked to CIM. Findings from the international study on CIM across 16 countries (37) revealed that England occupies the 7th position, while Portugal and Italy share the 14th position, as the countries in Europe with lower levels of CIM licenses. Although Italy shares the 14th place with Portugal in the European CIM rank, the bicycle culture seems to be more embedded in Italy where children learn to ride a bicycle earlier than in Portugal. Between 1800 and 1900 Italy was essentially an agricultural country and the most popular sport was cycling, which was considered a "symbol of progress". Now the bicycle is the most economical way of transport. ISTAT data from 2015 (43) showed that the bicycle was used by only 3.6% of the population and that cycling has increased unevenly on Italian territory. In Croatia, about 5% of all trips are made by bicycle and cycling is the least popular method of travel for going to work or to school (44). In Spain, only around 1.5% of children and 3% of adults cycle daily (45–48) and cycling is still classified as emerging (45). Portugal is the country in group 2 with the highest reported learning age. According to Shaw et al. (37), in Portugal bicycles play a scarce role on children's mobility—either alone or accompanied by parents—in terms of journeys between home and school. The reasons explaining the low levels of active and independent traveling in Portugal are related to stranger danger and the parents' perception of traffic hazards (49).

In countries from group 2, there have been efforts to promote sustainable mobility through the proliferation of soft modes of travel in urban centers and the planning of infrastructure to promote these behaviors (e.g., increasing bike lanes, bicycle share programs, etc.), and a number of cycling related community projects and initiatives have emerged [e.g., (50, 51)]. However, the majority of people opt for passive motor transport, with negative impact for health. Also, habits of using other modes of transport (i.e., passive motor transport) have a negative impact on bicycle use. Adults who use passive motor transport (i.e., car or motorbike) as the most frequent type of transport to commute are the most strongly opposed to cycling (52). Alternatively, leisure cyclists are likely to be commuter cyclists in the future (45, 52). So, increasing the cycling experience (in the leisure-time and/or sport activities) increases the valuation of attitudinal beliefs and decreases the barriers to cycling as a way of transportation.

Group 3 comprises the two Latin American countries in our study (Brazil and Mexico), in which children learned to cycle independently at a later age. Brazil and Mexico are the two only countries in our study that are not considered high-income countries according to the GDP data of the world bank (33). Possibly, buying a bicycle in these countries does not represent a priority in the families' domestic budget. In Brazil, until 1999, the use of bicycles was related to three aspects: (1) leisure, widespread in all socioeconomic levels; (2) competitive or non-competitive sporting activity; (3) toys, representing the development of motor skills and experiencing the first moments of freedom for children between 6 and 12 years old (53). In the last decade, there have been some changes to promote the use of bicycles (e.g., construction of bike lanes and implementation of bicycle sharing systems in large cities and in tourist cities). This has motivated families to encourage children to ride their bicycles before the age of 5/6; favoring the performance of leisure activities in the family, generating greater well-being and increased physical activity for all family members; in addition to the use of bicycles as a means of transport (urban mobility) by families of all socioeconomic levels (54).

In Mexico, the use of the bicycle does not seem to be popular or widespread. A recent study based on the national intercensal survey of 2015 (30), showed that although active transportation to school is fairly common among Mexican schoolchildren and adolescents, cycling is not (66.2% of the students walk to school whereas only 1.6% cycles). Moreover, when considering active and passive transportation modes, the bicycle falls into the last position in all states of Mexico.

Learning Age Over Generations

There could be some important and universal elements affecting the learning age for cycling (e.g., cooperation for learning, time on task, prompt feedback, etc.) that can be applied around the globe in diverse populations. Generation X learnt to cycle later than generation Z, which could be due to less financial availability of previous generations to acquire bicycles and to less shared leisure time between parents and children of those generations. In fact, parents and relatives of people in generation X had limited leisure time and consequently less time to support children in learning this motor task. Changes in the number of children per family, in the cultural ideals of parenthood and of parental levels of supervision and engagement in play should also be considered (55). For instance, it has been shown that younger siblings usually learn to cycle earlier than older siblings and only children (56). Homes, families and schools are powerful environments for empowering cycling enculturation (45). Specifically, family can be the social group with the most positive influence on the decision to use the bicycle (52) and/or learn to cycle. To do so, riding a bike should not only be seen as a mode of transport, guided by adult rationality, but as a form of active play, leisure, recreation or sport, which lays the foundation of positive practical experiences (45). Most children learn to cycle with the help of their families. Although structured programs with cycling lessons exist, they seem to be more frequent for children with disabilities (57). However, for all children, learning is enhanced when (1) it is more like a team effort than a solo race, (2) frequent opportunities to perform and receive suggestions for improvement exist and/or (3) learners use realistic amounts of time for effective learning (58). When a child persists, he/she can learn how to cycle. However, in addition to persistence, when the child is supported by an adult who provides feedback and encouragement to help him/her learn how to cycle, the path of learning might increase. In addition, the design of bicycles and their size have become more child-friendly across generations. It is possible that many children from generation X did not have access to bicycles correctly body-scaled to them (59), and instead they had to use adult bicycles. After entering the new millennium, our findings reveal another drop in the age that children learn how to cycle independently. Possibly, this is due not only to the more central place the bike adopts within the family context nowadays, but also due to the transition from learning how to cycle with training wheels to the use of the balance bikes (55, 60). In many countries, cycling is considered a traditional leisure time activity during childhood as many parents offer bikes to their children for playing when they are young. Moreover, cycling has become increasingly valued for its potential to improve physical literacy/motor skills and physical activity (61). Also, the greater importance that has been given in the recent decades to policies that promote healthy lifestyles and active transport (62) is probably another factor that influences the cycling learning age.

The results of the present study reveal the influence of changes in the macrosystem and chronosystem dimensions in proximal processes related to learning how to cycle, between generations X and Z. These changes are essential for the child to be able to cycle in the public space, alone or with other children, without adult supervision. This is one of the main licenses of independent mobility and a privileged component in a child-friendly community (63).

As a way of low-carbon city strategies around the World, policy and decision makers are engaged in the planning of initiatives that promote cycling (46) and there has been increased attention for cycling and its infrastructure to meet climate goals (64).

Learning Age Over Generations by Country

The bike is increasingly being considered an enjoyable, cheap, ecological and efficient mode of transportation, which promotes health and well-being. During youth, appropriate cycling promotion is associated with empowering confidence, knowledge, competence and attitudes (65).

Our findings revealed a significant interaction between country and generation indicating that generational changes differed slightly among countries with the decline in learning age being less evident in countries in which the learning age has been consistently low across generations.

It is not surprising that in countries from group 1 (especially in the Netherlands), the learning age has not changed as much over generations as in countries from group 2 or 3, in which investments in infra-structures and policies that promote cycling are more recent. However, it should be noted that the interaction effect was negligible ($\eta_p^2 = 0.006$). Whilst learning age for independent cycling is generally lower in later generations, countries generally maintained their rank relative to one another across time. Although national governments have increased their support for cycling in the past decades, there are other factors that may hinder or facilitate cycling. For instance, the perception of road safety has changed across generations, and fears about safety have often been mentioned as a reason to not cycle, especially in countries from group 2 (e.g., UK, see 18) and 3 (e.g., Mexico, see 30). The cycling culture and the efficacy of cycling campaigns also vary, and the plans for cycling investment are diverse (66). It is thus clear that policies and an urban planning framework that is friendly to the use of bicycle as an expressive daily travel mode by children and adults, as well as valuing the learning of cycling as an educational and developmental asset, are paramount for a widespread cycling culture and behavior.

Strengths and Limitations

To our knowledge, this is the first international study that examines the age for learning to cycle in different countries and across time. Additionally, this study has a large sample size, which was made possible through a web-based survey. However, some limitations need to be considered when interpreting the present findings. First, this cross-sectional study used retrospective self-report and parental reports, which are prone to response bias. Future studies should involve longitudinal designs to further understand when and how (young) children learn to cycle. Second, as participant recruitment took place *via* social media and with the help of different partners (e.g., parents' magazines, early childhood teachers' organizations, cycling federations and non-profit organizations), this may have led to sampling bias. For instance, members of cycling organizations will cycle more than the general populations in the respective countries, which might bias the average learning age for cycling within the study sample. Further research should consider personal/demographic factors (e.g., socio-economic status, ethnicity) and psychosocial factors (e.g., attitudes, habits, perceptions) to gain better insights into learning to cycle (67). Third, there were some large differences in sample size and variance between countries although unequal N HSD *post-hoc* tests have been used to address the issue of unequal group size and heterogeneity of variance. Finally, the present study focused on comparing learning ages for cycling among but not within countries. As cycling levels have been shown to vary within countries (68, 69), future studies should explore potential differences in learning age within countries and regions.

CONCLUSIONS

Learning to cycle is associated with physical, social and emotional benefits; as such, the earlier a child can ride a bike independently, the sooner they will experience those benefits. The present study specifically examined the influence of the macrosystem and chronosystem-as noted in Bronfenbrenner's bioecological theory (1995)-and their interaction, on the learning age of cycling. The interaction effect between country and generation was negligible, but our results show that the difference in age for learning to cycle independently can vary by about 3 years (usually between 4 and 7 years of age), depending on the country where the child lives (macrosystem) and the time of birth (chronosystem). A child from generation Z born in a high-income country where the bicycle use is culturally imbedded (e.g., the Netherlands or Finland), will on average learn to cycle independently at a much younger age than a child from generation X born in a middle-income country without a strong cycling culture (e.g., Brazil or Mexico). This latter group of countries would benefit the most from cycling promotion campaigns, policies that improve perceived public and road safety, and investments in infrastructures to promote active modes of transport. Finally, learning to cycle depends mostly on the child's microsystem—specifically, the face-to-face interactions between the children and the adults that support them to cycle. Our results indicate that the cycling culture, expressed by the cycling modal share that exists in a given country and a given time, seems to be closely related to the age at which children learn how to cycle, highlighting the interdependency between the different levels of a person's environment (19, 20).

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Ethics Committee of the Faculty of Human Kinetics (process number 22/2019). The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

RC, CM, MB, FL, and DC conceived the project and tested the first version of the survey. RC was responsible for a first data analysis and a first draft of the manuscript, but all authors contributed for the analysis and writing process and identified and recruited the international partners. All international partners (EH, AL, PT, GF, CS, BJ, LZ, AD, FB, RF, SV, SZ, and IE) examined the survey, reached a consensus for the final version, and were responsible for translating the survey and testing it in their own countries. All authors contributed to the dissemination of the survey in their own countries and read and approved the final manuscript.

FUNDING

RC, CM, and MB were partly supported by the Portuguese Foundation for Science and Technology, under Grant UIDB/00447/2020 to CIPER—Centro Interdisciplinar para o Estudo da Performance Humana (unit 447); DC was partly supported by the Portuguese Foundation for Science and Technology, under project No. UID/CED/04748/2020.

ACKNOWLEDGMENTS

Authors would like to thank the following organizations and people for their help in the survey's dissemination: Portuguese Cycling Federation, Estrelas e Ouriços Magazine and the Portuguese Association of Early Childhood Educators (APEI) (Portugal); Valentina La Cava, Daniele Faedda and Claudia Galassi (Italy); Cycling UK (UK); Pyöräliitto ry, Pyöräilykuntien verkosto ry and Jyväskylän Pyöräilyseura JYPS ry (Finland).

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TYPE Brief Research Report
PUBLISHED 04 October 2022
DOI 10.3389/fspor.2022.904924

Evaluation of the validity and reliability of the 10-meter walk test using a smartphone application among Japanese older adults

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OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Physical Activity in the Prevention and Management of Disease, a section of the journal Frontiers in Sports and Active Living

RECEIVED 28 March 2022
ACCEPTED 15 September 2022
PUBLISHED 04 October 2022

CITATION
Saito Y, Nakamura S, Tanaka A, Watanabe R, Narimatsu H and Chung U-i (2022) Evaluation of the validity and reliability of the 10-meter walk test using a smartphone application among Japanese older adults.
Front. Sports Act. Living 4:904924.
doi: 10.3389/fspor.2022.904924

Objective: Maintaining or improving regular walking speed can help extend healthy life expectancy and prevent frailty. The evaluation of walking speed can help individuals meet their daily exercise goals; therefore, it may be beneficial as a public health policy for residents to measure and evaluate their walking speed easily. This study aimed to verify the validity and reliability of a smartphone application for the 10-m walk test, measured in the general population.

Methods: The study participants were men (n = 20) and women (n = 20) aged 65–85 years. The 10-m walk tests were performed at the usual walking speed, using the stopwatch function of a newly developed smartphone application. A total of three 10-m walk tests were performed simultaneously with the study participants and professional fitness instructors to evaluate the criterion-related validity and the test-retest reliability.

Results: A strong positive correlation was found in the criterion-related validity by the study participants and professional staff for the average of the three trials {r = 0.961 [95% confidence interval (CI) = 0.927, 0.979]}. The results revealed good reliability, with an intraclass correlation coefficient of 0.712 (95% CI = 0.571, 0.823).

Conclusion: The smartphone application walking speed measurement method can be widely used by the general public and is useful for health promotion.

KEYWORDS
walking speed, smartphone application, mobile health (M-Health), public health, health promotion

Introduction

The 10-m walk test is widely used in preventive care and rehabilitation; it is evaluated by measuring speed and counting the number of steps taken within a given time. The measurement method includes walking a certain section set on a flat road at the usual or maximum speed, after which the walking time and number of steps taken are measured. Criterion-related validity has shown significant correlations in measurement methods (10 m and 4 m, stopwatch, and automatic timer) (1) and lower extremity muscle strength (sit-to-stand test) (2). Test-retest reliability by trained staff has also been high (1, 3).

Maintaining or improving usual walking speed is associated with reduction or prevention of mortality, hospitalization, activities of daily living ability, and cognitive decline (4, 5). Usual walking speed is used as a criterion for assessing frailty and sarcopenia, which are associated with a high risk of care dependency. In Asian countries, sarcopenia is defined as a low walking speed of <1.0 m/s (6). The minimum clinically meaningful change in normal walking speed is 0.05 m/s, which is an indicator of the effect of treatment on an individual, while a substantial change is reported at 0.10 m/s (7).

The evaluation of walking speed is beneficial for extending healthy life expectancy; therefore, it may be a helpful public health policy for residents to easily measure and evaluate it. Furthermore, implementing a method that can be easily performed using a smartphone application is expected to be quickly adopted in a healthcare set-up.

In response to this situation, the ME-BYO index was implemented in Kanagawa Prefecture, one of the biggest local governments in Japan, that measured the ME-BYO in the health management application, My ME-BYO Record, in March 2020 (8). ME-BYO is a concept that does not consider health and sickness as two separable conditions; it is a concept that covers the entire process of continuous change in the physical and mental condition between health and sickness (8).

The ME-BYO index visualizes an individual's current state of the ME-BYO and future disease risk in numerical form. It comprehensively quantifies the domains of lifestyle, physical function, cognitive function, mental health, and stress. The ME-BYO index was developed based on evidence and discussion among experts. Specific evaluation items included gender, age, body mass index, systolic blood pressure (lifestyle), Mini-Cog (cognitive function) (9), locomotive function (10), walking speed (physical function), and mind-monitoring system (mental health and stress) (11).

Abbreviations: ICC, intraclass correlation coefficient; CIs, confidence intervals; WHO ICOPE, World Health Organization Integrated care for older people.

To assess walking speed, a 10-m walk test (12) with a stopwatch function was adopted. This study aimed to verify the validity and reliability of the 10-m walk test measured by the general population.

Methods

Study participants

Forty target participants (20 men and 20 women) aged 65–85 years were included in the study. They attended health promotion facilities on their own and performed exercises. In the sample size design, assuming a significance level of 5%, power of 80%, and effect size of 0.5, the required number of participants was 29. The final number of study participants was set at 40, assuming dropouts and multiple applicants signed up at the same time.

This study was approved by the Research Ethics Committee of the Graduate School of Health Innovation, Kanagawa University of Human Services (approval no. Hodai 30–011). The purpose and content of the study were explained to the study participants, and written informed consent was obtained from them before the study was conducted.

Measurement items

The 10-M walk test using the application by the study participants

The study participants measured their walking speed using a smartphone equipped with the ME-BYO index application for research (Supplementary Figure 1). The research application was designed to store data locally on the device. The ME-BYO index for general use is implemented in the My ME-BYO Record application, which can be downloaded from the App Store.

For the 10-m walk test, the participants followed the on-screen instructions to walk 10 m at their usual speed, and the walking time was measured. The site was a flat indoor area with 4-m preliminary and deceleration zones. The time taken for the 10-m walk was measured using the stopwatch function in the application. Before starting the measurement, the participants waited in a stationary standing position at the starting point of the preliminary zone. The participants walked to the goal point of the deceleration path (18 m) without stopping at the end of 10 m.

Measurements were taken by tapping the screen as soon as either toe crossed the line between the start and end lines. If the speed was faster or slower than the usual walking speed, the participant was asked to confirm and re-measure. Walking time was measured to the nearest hundredth of a second. The walking speed was calculated by dividing the distance (10 m) by the walking time (m/s).

The 10-M walk test by professional staff

To verify the criterion-related validity, the measurements by the professional staff and the study participants were simultaneously conducted. The measurement was conducted by a health fitness instructor with sufficient knowledge and experience in using the stopwatch method, which is widely used in clinical practice (ALBA PICCO Standard, manufactured by SEIKO, Tokyo, Japan). The timing of starting and ending the stopwatch was the same as that of the study participants.

The staff walked diagonally behind the study participants to avoid guiding the study participants. The distance between the study participant and the instructor was not too large so that the instructor could immediately support the participant in case of a fall and did not interfere with the study participant's walking.

Five-time sit-to-stand test

The five-time sit-to-stand test (13) required participants to stand up from and sit down on a slightly padded 42-cm high armless chair as quickly as possible five times. Participants folded their arms across their chests and were instructed to stand up completely and make firm contact with the chair when sitting. The commencement time began on the command "go" and ceased when the participants sat after the fifth stand-up. Participants were allowed a practice trial of one to two repetitions before the test trial. The measurements were taken by a health fitness instructor who used a stopwatch to measure the time to 1/100th of a second, rounded off to the nearest tenth of a second.

Basic attributes

The following information was obtained for the measurement items of the ME-BYO index application: sex, date of birth (age), height, weight, and blood pressure. These items were measured before the 10-m walk test. Data on educational attainment, working status, and living arrangement were obtained using a questionnaire.

Statistical analysis

The normality of the walk test was analyzed using the Shapiro–Wilk test. The criterion-related validity of the walk test was assessed by Pearson's correlation coefficient for the speed (m/s) of the 10-m walk in the ME-BYO index application performed by the study participants and health fitness instructors. The second value and average of the three values were employed to validate the walk test, as in previous studies (1). Test-retest reliability was assessed using intraclass correlation coefficient (ICC) and 95% confidence intervals (CIs). For test-retest reliability, the values of all three tests were used. For the statistical analysis, SPSS version 27 (IBM, Tokyo, Japan) software was used. The significance level was set at 5%.

Results

Basic attributes

This study included 40 participants (20 men and 20 women) with a mean age (standard deviation) of 74.9 (5.2) years. Other participant characteristics are shown in Table 1.

The mean values (standard deviations) of the three trials of the participants and the health fitness instructor in the 10-m walking speed were 1.43 (0.1) m/s and 1.43 (0.1) m/s for men and women, respectively. All walk tests were normal distribution.

Validity and reliability of the 10-M walk test by study participants and professional staff

The results of the validity and reliability of the 10-m walk test are shown in Table 2. As a result of the criterion-related validity of the walking speed of the ME-BYO index application measured by the study participants and health fitness instructors, Pearson's correlation coefficient was $r = 0.862$ (95% CI = 0.753, 0.925), $P < 0.001$ for the second trial, and $r = 0.961$ (95% CI = 0.927, 0.979), $P < 0.001$ for the average of the three trials, indicating a significantly strong positive correlation.

The ICC (95% CI) for test-retest reliability was 0.712 (0.571, 0.823), $P < 0.001$, indicating moderate reliability.

Validity of the 10-M walk test measured by study participants and five-time sit-to-stand test measured by professional staff

The criterion-related validity of the walking speed of the ME-BYO index application measured by the research participants and the five-time sit-to-stand test measured by health fitness instructors was examined. Pearson's correlation coefficient was $r = -0.572$ (95% CI = −0.750, −0.317), $P < 0.001$ for the second trial, and $r = -0.579$ (95% CI = −0.754, −0.326), $P < 0.001$ for the average of the three trials, indicating a significant positive correlation.

Discussion

This study examined the validity and reliability of a method in which the general population underwent the 10-m walk test, which is generally conducted at the usual walking speed, using the stopwatch function of a smartphone application. A strong positive correlation was found in criterion-related validity with the method measured by professional staff (health fitness instructors). In previous studies, a moderate correlation

TABLE 1 Characteristics of the study participants.

	Men ($n = 20$)		Women ($n = 20$)		Total ($n = 40$)	
Age, years	75.3	(5.3)	74.6	(5.2)	74.9	(5.2)
Educational attainment, n (%)						
<13 years	8	(40.0)	10	(50.0)	18	(45.0)
≥13 years	12	(60.0)	9	(45.0)	21	(52.5)
Missing	0	(0)	1	(5.0)	1	(2.5)
Working status, n (%)						
Working with income	6	(30.0)	5	(25.0)	11	(27.5)
Not working	14	(70.0)	14	(70.0)	28	(70.0)
Missing	0	(0)	1	(5.0)	1	(2.5)
Living arrangement, n (%)						
With others	19	(95.0)	16	(80.0)	35	(87.5)
Alone	1	(5.0)	3	(15.0)	4	(10.0)
Missing	0	(0)	1	(5.0)	1	(2.5)
Height, cm	166.2	(7.7)	153.2	(6.4)	159.7	9.6
Body weight, kg	63.9	7.7	49.8	4.8	56.8	9.6
Body mass index, kg/m^2	23.1	(1.7)	21.2	(2.1)	22.2	(2.1)
Systolic blood pressure, mmHg	138.4	(13.3)	131.8	(18.7)	135.1	(16.3)
Diastolic blood pressure, mmHg	75.7	(10.5)	71.4	(9.5)	73.5	(10.1)
Average walking speed (Participants), m/sec	1.40	(0.1)	1.46	(0.1)	1.43	(0.1)
Average walking speed (Health fitness instructor), m/sec	1.40	(0.1)	1.46	(0.1)	1.43	(0.1)
5-times sit-to-stand test, sec	6.9	(2.2)	5.1	(0.9)	6.0	(1.9)

Mean (standard deviations).

TABLE 2 Validity and reliability of the 10-meter walk test by study participants and professional staff.

	Criterion-related validity			Test-retest reliability		
	r	95% CI	*P*	ICC	95% CI	*P*
Walking speed: second trial	0.862	0.753, 0.925	<0.001	0.712	0.571, 0.823	<0.001
Walking speed: average of three trials	0.961	0.927, 0.979	<0.001			

Criterion-related validity: Pearson's correlation coefficient. Test-retest reliability: ICC (1, 1). ICC, Intraclass correlation coefficient; CI, confidence interval.

was found in the validity of the five-times sit-to-stand test (2), which has been adopted as an evaluation index for sarcopenia (6) and the World Health Organization Integrated care for older people (WHO ICOPE) guidelines (14); this method also has good reliability. In locations with no space to measure the walk test, the five-time sit-to-stand test was an option. Furthermore, in the Bland–Altman analysis, the agreement between professional staff and participants was high, and the systematic error was within range (Supplementary Figure 2). Subgroup analysis based on sex and blood pressure also showed similar results (Supplementary Tables 1, 2). These results suggest that the smartphone application measurement method can be widely used by the general public and is useful for health promotion.

The validity and reliability of the 10-m walk test and the 4-m walk test, measured by professional staff, have been studied. The validity and reliability of these studies were comparable to that of the present study (1). The reliability of the 4-, 6-, and 10-m walk tests with the usual pace measured by trained staff in older adults (3) was also similar to that of this study (ICC 0.72–0.90). Considering that our results were comparable to previous studies and that this study was conducted among the general population, it suggests that health promotion activities for residents can be expanded using the measurement methods used in this study. Moreover, high validity and reliability were confirmed among the older adults, and the results can be generalized to the younger generation, most of whom use smartphones.

Conversely, the 10-m walk test requires a place for measurement. When this application is disseminated, it is necessary to improve the environment where the measurements are obtained so that it can be conducted in community parks and exercise facilities. Furthermore, an application for the automatic measurement of walking speed with a patented technology using the global positioning system function has been implemented (15), and it is necessary to consider using it in conjunction with such technology.

One of the limitations of this study is that it did not involve random sampling and only included healthy, older adults with relatively high walking speeds. Therefore, caution should be exercised when implementing the insights generated in this study on residents with low cognitive function and locomotive impairments.

In conclusion, we confirmed the validity and reliability of a 10-m walk test application measured by the residents using the stopwatch function of a smartphone application. Moreover, the results were equally favorable for sex and the population with hypertension. This application has sufficient scientific validity to be measured by residents and can be used as motivation to maintain and improve health behavior.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by Research Ethics Committee of the Graduate School of Health Innovation, Kanagawa University of Human Services (approval no. Hodai 30-011). The patients/participants provided their written informed consent to participate in this study.

Author contributions

YS: conceptualization, methodology, formal analysis, investigation, data curation, writing–original draft, writing–review and editing, and project administration. SN: conceptualization, methodology, and writing–review and editing. AT: investigation and writing–review and editing. RW: conceptualization and writing–review and editing. HN: conceptualization, methodology, writing–review and editing, supervision, project administration, and funding acquisition. UC: conceptualization, writing–review and editing, supervision, and funding acquisition. All authors have read and approved the final manuscript.

Funding

This study was supported by the ME-BYO index project of the Kanagawa Prefecture and Grants-in-Aid for the Japan Society for the Promotion of Science (JSPS) KAKENHI Grant [No. 16H06277 (CoBiA)] from the Japanese Ministry of Education, Culture, Sports, Science, and Technology.

Acknowledgments

We are grateful to the residents who participated in this study. The authors would like to acknowledge Hygeia Communication for their support with the research management. We thank Editage (www.editage.jp) for English language editing.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fspor.2022.904924/full#supplementary-material

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frontiers | Frontiers in Sports and Active Living

TYPE Systematic Review
PUBLISHED 19 October 2022
DOI 10.3389/fspor.2022.1031004

Check for updates

OPEN ACCESS

EDITED BY
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SPECIALTY SECTION
This article was submitted to Physical Activity in the Prevention and Management of Disease, a section of the journal Frontiers in Sports and Active Living

RECEIVED 29 August 2022
ACCEPTED 04 October 2022
PUBLISHED 19 October 2022

CITATION
Riiser A, Bere E, Andersen LB and Nordengen S (2022) E-cycling and health benefits: A systematic literature review with meta-analyses.
Front. Sports Act. Living 4:1031004.
doi: 10.3389/fspor.2022.1031004

E-cycling and health benefits: A systematic literature review with meta-analyses

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The objective of the present study is to review and meta-analyze the effect of E-cycling on health outcomes. We included longitudinal experimental and cohort studies investigating the effect of E-cycling on health outcomes. The studies were identified from the seven electronic databases: Web of Science, Scopus, Medline, Embase, PsycINFO, Cinahl and SportDiscus and risk of bias was assessed with the revised Cochrane Collaboration Risk of Bias Tool (RoB2). We performed meta-analysis with random effects models on outcomes presented in more than one study. Our study includes one randomized controlled trial, five quasi experimental trials and two longitudinal cohort studies. The trials included 214 subjects of whom 77 were included in control groups, and the cohort studies included 10,222 respondents at baseline. Maximal oxygen consumption and maximal power output were assessed in four and tree trials including 78 and 57 subjects, respectively. E-cycling increased maximal oxygen consumption and maximal power output with 0.48 SMD (95%CI 0.16–0.80) and 0.62 SMD (95%CI 0.24–0.99). One trial reported a decrease in 2-h post plasma glucoses from 5.53 ± 1.18 to 5.03 ± 0.91 mmol L^{-1} and one cohort study reported that obese respondents performed 0.21 times more trips on E-bike than respondents with normal weight. All the included studies had a high risk of bias due to flaws in randomization. However, the outcomes investigated in most studies showed that E-cycling can improve health.

KEYWORDS

active transportation, E-bicycle, health, fitness, meta-analysis

Introduction

Cycling is regarded a good form for physical activity and cycling conventional bikes has positively been related to health outcomes. In the two systematic reviews with meta-analyses of Nordengen et al.

10.3389/fspor.2022.1031004

(1, 2), cyclists were associated with 16% risk reduction in cardio vascular disease (CVD) incidence and CVD mortality, and a 25% risk reduction of CVD risk factors as elevated blood pressure, overweight and obesity, low fitness, and unfavorable blood lipid profile.

We are in an electrically assisted bicycle (E-bike) revolution. Sales of E-bikes in Europe has increased from 0.5 million in 2009 to 3 million in 2019 (3), and they are steadily increasing to 4.5 million in 2021 (4). E-bikes differ from conventional bikes as they provide electrically powered assistance when riding. There are two different types of E-bikes; both where pedaling is required to get assistance and E-bikes that do not require pedaling (5). The present review will only refer to E-bikes as E-bikes which require the rider to pedal.

E-cycling compared to cycling is less intensive, however, the intensity is still within the intensity range for physical activity recommended by the WHO to obtain significant health benefits and mitigate health risks (6, 7). E-cycling could therefore help individuals meet physical activity recommendations. Several studies report that people cycle more and longer distances with an E-bike (6, 8). If E-cycling contributes significantly to the recommended 150 min per week with moderate physical activity, using an E-bike might therefore result in improved health. The E-bike might also shift mode of transport from car dependence (9), reducing man-made climate gas emissions.

A recent review and meta-analysis quantified the difference in acute physiological responses between E-cycling with electrical assistance, E-cycling without assistance, conventional cycling, and walking. Heart rate, oxygen consumption, and metabolic equivalents responses were lower when E-cycling compared to conventional cycling. However, E-cycling was associated with moderate to vigorous physical activity. E-cycling was also performed with a higher heart rate and oxygen uptake than walking and they concluded that E-cycling was associated with increased physiological responses that can confer health benefits (10). However, the impact of physiological and mental health arising from riding an E-bike is still inconclusive (3).

As demonstrated in several cross-sectional studies and acute experiments E-cycling has a great potential in improving health. However, few long-term studies have been conducted regarding the health effect of using E-bikes. Therefore, the objective of the present study is to review and meta-analyze the effect of E-bikes on health outcomes including intervention studies and longitudinal cohort studies.

Methods

We performed a systematic review and meta-analysis according to the PRISMA 2020 guidelines (11). The research protocol for this systematic review with meta-analyses was registered at PROSPERO on 12 April 2022, with registration number CRD42022316485.

Search strategy and selection criteria

Literature search

We selected the 17 studies identified by "Health benefits of electrically-assisted cycling: a systematic review" (12). In addition a university librarian systematically reproduced the search performed by Bourne et al. (12) and searched for studies published in the period from 2018 to 7th of March 2022. Peer reviewed publications in English were identified from the seven electronic databases: Web of Science, Scopus, Medline, Embase, PsycINFO, Cinahl and SportDiscus. The search consisted of the search terms "pedelec," "E-bike," "electrically assisted bicycle," "electrically assisted cycle," "electrically assisted bike," "pedal-assist," "electric bicycle," "electric bike," "electric cycle," "electric mobility." For full search strategy see Supplementary Table 1.

Inclusion criteria and the selection process

Two authors (SN and LBA) independently screened the 3,481 records on basis of title/abstract for eligibility and assessed 34 full text articles for eligibility. Discrepancies were resolved by discussion. We included experimental, quasi-experimental and cohort studies with a longitudinal design investigating the effect of E-cycling on outcomes related to health. Experimental studies were considered longitudinal if they investigated the effect of an intervention lasting more than 1 week and cohort studies were considered longitudinal if the cohorts were investigated more than once. Studies were eligible for inclusion if they included healthy participants ≥18 years of age and the electrically assisted bicycles had pedals and was operated by the individual, with assistance available from an electric motor. Studies examining outcomes related to cardiorespiratory fitness, like maximal oxygen consumption and maximal power output in an incremental trial, physiological outcomes like blood pressure and blood lipids, and questionnaire-based outcomes from validated questions/questionnaires aiming to assess mental and physical health were included. Studies comparing E-cycling to no control group, conventional cycling, passive transport, public transport, "business as usual" and walking were included. Field studies investigating the acute effect of E-cycling, observational studies, and studies on patient populations like heart disease and type 2 diabetes were excluded while overweight populations were included.

Analysis

One authors (AR) extracted data from the included studies. Meta-analyses were performed when the same outcomes were reported in two or more studies and if the studies had a similar comparator (conventional bicycle was considered on type of comparator and passive travel group and no cycling control group was considered on type of comparator) regardless of length of the intervention, amount of cycling, or type of e-bike used in the intervention. In trials without a control group the change in the experimental group was compared to a hypothetical group with size and standard deviation equal to the experimental group and a change in the outcome of interest set to zero. These trials were meta-analyzed with trials with passive travel group and no cycling control group. The study by Hochmann et al. (13) is a randomized controlled trial (RCT) comparing the effects of E-cycling with conventional cycling. This is the only study with physiological outcomes and comparing it to conventional cycling. Thus, to include the results from this study in the meta-analysis, the results were compared with a hypothetical control group with size and standard deviation equal to the experimental group and change from pre to post of zero (the same procedure as we used with studies without a control group).

Study quality assessment

The included studies were assessed using the five domains of the revised Cochrane Collaboration Risk of Bias Tool (RoB2) (14). The tool is developed for randomized controlled trials, but we used the same tool for all included studies. According to the tool criteria each domain was scored as low risk of bias, some concerns or high risk of bias. The domains in the tool are Risk of bias (1) arising from the randomization process, (2) arising from period and carryover effects, (3) due to deviations from the intended interventions, (4) due to missing outcome data, (5) in measurement of the outcome, (6) in selection of the reported result. Overall risk of bias for each study was determined by the highest risk of bias across all domains. Two authors (EB and LA) independently assessed the included studies and discrepancies in the assessment were resolved by discussion.

Statistics

We performed meta-analysis with random effects models as we deemed the included studies to be heterogeneous with regards to interventions, study designs, and populations. We used Comprehensive Meta-Analysis (CMA) V3 (Biostat, Englewood, New Jersey, USA) to perform meta-analysis. Only one outcome per study was included in each meta-analysis

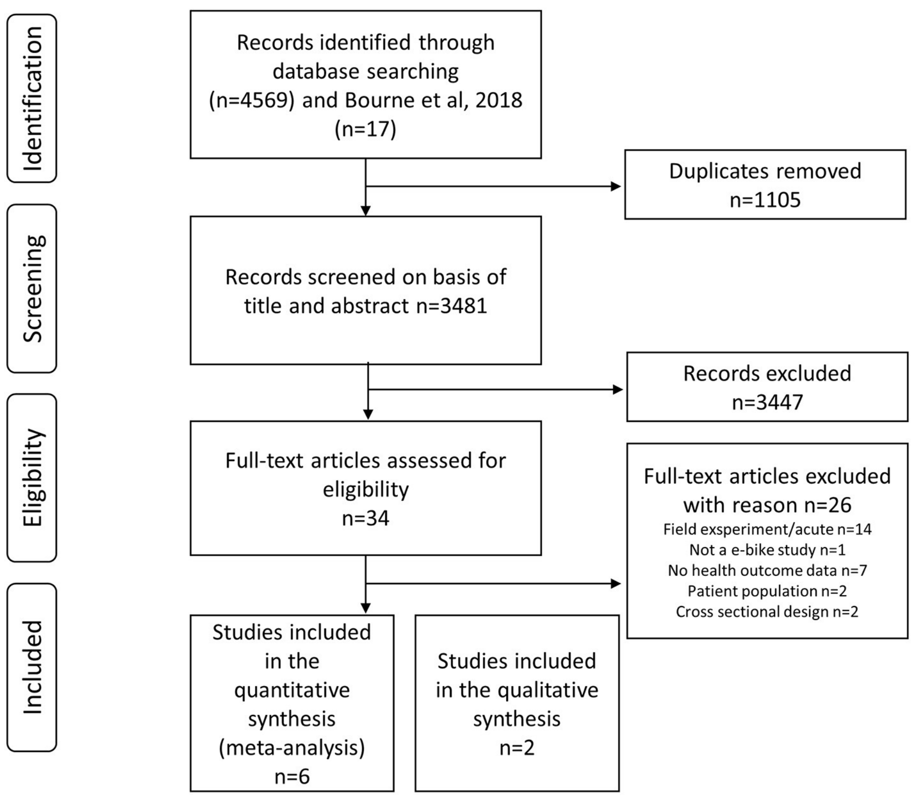

FIGURE 1
Flow chart of included studies as proposed by Preferred Reporting Items for Systematic Reviews and Meta-Analyses statement 2020.

and only the same outcomes from different studies were meta-analyzed. Effect estimates were presented as standardized mean difference (SMD) with 95% confidence intervals (CI) and in forest plots. Heterogeneity was reported as I^2 and p-values. Significance level was set to $p < 0.05$.

Results

Study characteristics

The search identified 4,569 records (Web of Science 1328, Scopus 2533, Medline 221, Embase 239, PsycINFO 54, Cinahl 60, SportDiscus 134 records). After automatic elimination of duplicates, 3,481 records remained. Thirty four studies were selected for full-text eligibility assessment after screening of titles and abstracts (Figure 1).

In total eight studies were included in the systematic review (13, 15–21). We included one randomized controlled trial (13) and five quasi experimental trials, where one of the quasi experimental trials had a pseudo randomized control group (15), and the remaining four had no control group (16–19). We also included two longitudinal cohort studies (20, 21) investigating the association between E-cycling and health outcomes. The trials were performed in Switzerland, UK (x2), Norway, Belgium and USA and included 214 subjects of whom 77 subjects were included in control groups. Four trials investigated the effect of E-cycling on cardiorespiratory fitness, two the effect on body mass index (BMI), two the effect on blood pressure and two studies investigated the effect of E-cycling on mental health using the short form of the Global Health Questionnaire (GHQ12) (22) or the short form Health Survey (SF36) (23). One cohort study was from the Netherland and the other was a multicentre study from seven European cities. For characteristics of the included studies see Table 1.

Risk of bias

The randomized controlled trial (13) was considered to have low risk of bias while the five quasi experimental studies (15–19) and both observational studies were considered to have high risk of bias arising from the lack of randomization process. However, the RCT was analyzed with a hypothetical control group (no cycling) when included in the meta-analysis, because the control group included in the study did conventional cycling, and the RCT therefore was considered as high risk of bias in the meta-analysis. In Table 3, we present SMD from the RCT only and there the study has low risk of bias. None of the included studies indicated if the study protocol was pre-registered or not.

Meta-analysis of the effect of E-cycling on health

Six health related outcomes were assessed in two or more included studies and were meta-analyzed. Maximal oxygen consumption (Figure 2) and maximal power output (Figure 3) increased from before to after a period with commuting with E-bike. Body mass index and blood pressure remained unchanged (Table 2). The SMD of the scores from the questionnaires assessing health also remained unchanged. The effects of the two included studies were heterogeneous.

The health outcomes total cholesterol, low density lipoprotein (LDL), high density lipoprotein (HDL), triglycerides, fasting plasma glucose and 2-h post plasma glucose was assessed by Peterman et al. (19) and they reported a decrease ($p < 0.05$) in 2-h post plasma glucoses from 5.53 ± 1.18 to 5.03 ± 0.91 mmol L^{-1}.

The effect of E-cycling compared to conventional cycling

Two studies (13, 15) compared the effect of E-cycling to conventional cycling. These studies found no difference in VO_{2-max}, maximal power, mental health, BMI, DBP and SBP ($p > 0.243$) (Table 3).

Results from longitudinal observational studies

de Haas et al. (21) reported that obese people perform 0.21 times more E-bike trips than normal weight people. Obesity was not associated with E-bike distance in the same study. Self-perceived health ("How would you rate your health in general?"), or overweight was not associated with E-cycling (20, 21).

Discussion

The aim of the present systematic review with meta-analysis was to assess the effect of E-cycling on health. We included six experimental studies with a longitudinal design (13, 15–19) and two longitudinal observational studies (20, 21). We found that regularly E-cycling improved aerobic fitness, which is an important predictor for health. There was no evidence for change in perceived physical health, BMI, systolic blood pressure or diastolic blood pressure when all available evidence was aggregated.

The meta-analysis includes only experimental trials which is considered to produce high quality evidence. The gold standard for experimental trials is randomized controlled trials and

TABLE 1 Characteristics of the included studies.

Study	Study design	Duration	Participants, Gender, age (years)	Intervention/behavior of interest	Comparators	Outcomes
Hochsmann et al. (13)	RCT, Switzerland	4 weeks	28 m/4 f 17 E-bike, 37 year (IQR 34, 45) 15 Conventional bike (37 year) (IQR 38, 45) Overweight	E-bike up to 250 W, active commute to work at a self-chosen speed on at least 3 days per week	Conventional bike	VO_2-peak Max watt Body mass SBP DBP HR at rest BMI
Leyland et al. (15)	Quasi-experimental, United Kingdom	8 weeks	100 (50–83 year), 38 E-bike, 26 non cyclist, 36 conventional bike Older adults	E-bike Required to cycle at least three times a week for 30 mins	Conventional bike, passive travel	Mental health Physical health
Page et al. (16)	Quasi-experimental, United Kingdom	Median 6 weeks, range 3–8 weeks	4 m/17 f, 21–55 yr	Multicomponent intervention including possibility to borrow E-bike free of charge	Passive travel	Physical health (self-report)
Lobben et al. (18)	Quasi-experimental, Norway	3–8 months	21 (baseline 7m/18f), 44 ± 7 year	Access to E-bike	No control group	VO_2-max
de Geus et al. (17)	Quasi-experimental, Belgium	6 weeks	10 m, 10 f 45 yr ± 7/43 yr ± 6	Use E-bike at least 3 times per week to and from work 405 ± 156 km	4 weeks control period	VO_2-peak Max watt BMI
Peterman et al. (19)	Quasi-experimental, USA	4 weeks	14 f/6 m 41.5 ± 11.5 yr	Commute with E-bike at least 3 days per week for 40 min per day	No control group	VO_2max Max watt SBP DBP
Avila-Palencia et al. (20)	Observational Longitudinal study and cross-sectional Seven European cities	From November 2014 to November 2016.	Baseline 8,802, 53% f, 38 yr Follow-up 3,567, 53% f, 41 yr	E-cycling, days per month	Unclear	Self-perceived health

(Continued)

TABLE 1 (Continued)

Study	Study design	Duration	Participants, Gender, age (years)	Intervention/behavior of interest	Comparators	Outcomes
de Haas et al. (21)	Observational longitudinal study, The Netherlands	2017–2019	1,420 52% f, adults	E-cycling	Passive transport	Overweight obesity Self-perceived health

BMI, body mass index; f, female; m, male; SBP, systolic blood pressure; DBP, diastolic blood pressure; yr, year.

Study name	Comparison	Outcome	Std diff in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Lobben, 2018	No control	VO2peak/max (ml)	0,936	0,325	0,106	0,299	1,573	2,880	0,004
De Geus, 2013 women	No control	VO2peak/max (l)	0,338	0,450	0,203	-0,544	1,221	0,751	0,452
Peterman, 2016	No control	VO2peak/max (l)	0,346	0,319	0,101	-0,278	0,971	1,087	0,277
De Geus, 2013 men	No control	VO2peak/max (l)	0,089	0,447	0,200	-0,788	0,966	0,200	0,842
Hochmann, 2018nc	No control	VO2peak/max (ml)	0,434	0,347	0,120	-0,246	1,114	1,250	0,211
			0,479	0,163	0,027	0,159	0,799	2,935	0,003

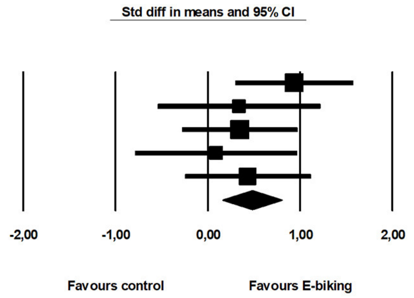

FIGURE 2
Forest plot for the effect of E-cycling on maximal oxygen consumption.

Study name	Comparison	Outcome	Std diff in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
De Geus, 2013 women	No control	Max power (w/kg)	0,667	0,459	0,211	-0,234	1,567	1,451	0,147
Peterman, 2016	No control	Max power (w)	0,634	0,324	0,105	-0,002	1,269	1,955	0,051
De Geus, 2013 men	No control	Max power (w/kg)	0,750	0,463	0,214	-0,157	1,657	1,621	0,105
Hochmann, 2018nc	No control	Max power (w)	0,500	0,348	0,121	-0,183	1,183	1,435	0,151
			0,619	0,192	0,037	0,243	0,995	3,226	0,001

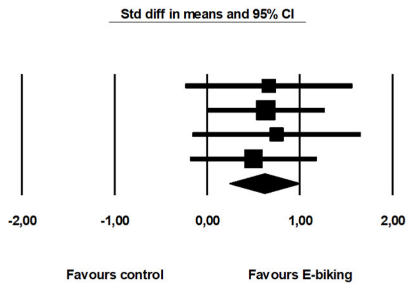

FIGURE 3
Forest plot for the effect of E-cycling on maximal power output during cycling.

we used a quality assessment tool developed for randomized controlled trials. However, only one of our trials were properly randomized and controlled. Thus, five out of six trials were categorized as having a high risk of bias. The trial with low risk of bias compared the effect of E-cycling to conventional cycling as the only study assessing physiological outcomes. Thus, we could not use the control group in the meta-analysis which introduced a high risk of bias in this study as well.

The most studied outcomes were maximal oxygen consumption (VO_2-max) and maximal power output. Using an E-bike increased these parameters 0.48 SD and 0.62 SD, respectively. This translates into an increase of around 10% in aerobic performance or 3.5 ml O_2 min^{-1} kg^{-1}. An increase of this size will improve health and Kodama et al. (24) found a decrease in all-cause mortality of 13% for this increase in fitness. Intuitively we would expect conventional cycling was performed at a higher intensity than E-cycling and therefore would result in

TABLE 2 Meta-analysis for the effect of E-cycling on health outcomes.

Outcome	Studies/subjects	Meta-analysis			Test of heterogeneity	
		SMD	95%CI	*P* value	I^2 (%)	*p*
VO_2peak/max	4/78	0.48	0.16 to 0.80	0.003	0	0.554
Max power	3/57	0.62	0.24 to 0.99	0.001	0	0.976
Physical health	2/85	0.70	−0.41 to 1.81	0.216	82	0.021
BMI	2/37	−0.06	−0.51 to 0.40	0.802	0	0.858
DBP	2/37	−0.06	−0.52 to 0.40	0.783	0	0.913
SBP	2/37	−0.12	−0.57 to 0.34	0.903	0	0.605

VO_2peak/max, maximal oxygen consumption; Max power, maximal power output during an incremental endurance trial; BMI, body mass index; DBP, diastolic blood pressure; SBP, systolic blood pressure; SMD, standardized mean difference.

TABLE 3 The effect of E-cycling compared to conventional cycling.

Outcome	Subjects, E-bike/bike	SMD	95%CI	*p*
VO_2-peak/max	17/15	0.19	−0.54 to 0.91	0.611
Max power	17/15	0.00	−0.72 to 0.72	1.00
Mental health	38/36	0.27	−0.19 to 0.73	0.244
BMI	17/15	−0.08	−0.80 to 0.65	0.838
DBP	17/15	0.34	−0.39 to 1.07	0.356
SBP	17/15	0.20	−0.52 to 0.93	0.581

All outcomes are assessed in one study (13) only. A positive SMD would indicate positive change in favor of E-bike.
VO_2peak/max, maximal oxygen consumption; Max power, maximal power output during an incremental endurance trial; BMI, body mass index; DBP, diastolic blood pressure; SBP, systolic blood pressure; SMD, standardized mean difference.

greater improvements in fitness and general health. However, we speculate that when people commute, they choose a self-selected speed where they feel comfortable, because most do not want to get to work sweaty. This may apply to both conventional and E-cycling which may explain why the relative workload is almost the same. Bourne et al. (12) reported in their review similar relative intensity during E-cycling and conventional biking. The oxygen consumption ranged between 51 and 73% VO_2-max for E-cycling and 58–74% of VO_2-max for E-cycling conventional cycling. Nordengen et al. (1) found in a meta-analysis a 0.28 SMD in cardio respiratory fitness comparing conventional cyclists with non-cyclists, and if E-cycling provides physical activity with similar intensity it supports the findings from the present study, demonstrating improved fitness from E-cycling. Similarly, Møller et al. (2011) found an increase in VO_2-max of 2.6 ml O_2/min/kg (0.5 SMD) between conventional cycling and a control group in a randomized trial (25).

Other health outcomes such as blood pressure (13, 19), BMI (13, 19) and self-reported physical health (15, 16) were only assessed in two trials and total cholesterol, LDL, HDL, triglycerides, fasting plasma glucose and 2-h post plasma glucose were only assessed in one study (19). It is therefore premature to conclude the effect of E-cycling on these outcomes. Different aspects of mental and perceived health were measured in both the experimental (15, 16) and observational studies (20, 21) included in the present systematic review. However, the included studies did not find any association between mental or perceived health, and E-cycling. Previous experimental (26) and observational (20) studies have reported conventional cycling to be positively associated with mental and perceived health (20). Thus, it may seem plausible that E-cycling is associated with mental and perceived health. Our data has several weaknesses and it is therefore premature to conclude on these outcomes as well.

The strength of this review is a quantification of health effects of E-cycling in longitudinal studies. However, only one study was a randomized trial and they used conventional cycling as control. We analyzed uncontrolled longitudinal studies with a fictive control group with no change. Results should therefore be interpreted with caution. It is a weakness that all included studies had high risk of bias, and we would highly recommend future studies should be conducted as randomized controlled studies. The included studies have large variations in intervention period, type of E-bike and amount of cycling leading to great variation in exposure/physical activity. There is a dose-response relationship between physical activity and health outcomes where more physical activity is associated with better heath (7). This dose response relationship may explain why the included studies have different effect size. Another weakness is that we used RoB2, a tool intended for RCTs even if studies we identified and included were mainly not RCTs. However, the first domain in the tool "Was the allocation sequence random?" was appropriate to identify that all studies had a high risk of bias. The study included only peer reviewed studies published in English, thus there is a possibility that we have failed to include relevant studies. Still, data points against an improvement in aerobic fitness from E-cycling, and the size of the improvement is sufficient to improve health.

During the last decade sales of E-bikes has increased substantially (4) as has the use of E-bikes (19). Commuting by

E-bike is a mode of active transportation providing everyday physical activity. Commuting by E-bike has a potential to improve health and we think it is surprising that there are so few longitudinal studies and only one randomized trial which investigate health effects of E-cycling. Thus, we recommend that there should be conducted more RCTs with a control group and proper randomisations investigating the effect of E-cycling over weeks or months. All health-related outcomes are of interest as long as they are assessed with valid and sensitive methods. Questions related to E-cycling should also be included in cohorts investigating health outcomes in different populations making ground for longitudinal observational studies investigating the relationships between E-cycling and health.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

AR drafted the methods and results section, extracted data, performed the analysis, and finalized the manuscript. SN wrote the protocol, designed the literature search, identified eligible studies (with LA), and approved the final manuscript. LA identified eligible studies (with SN), assessed risk of bias (with EB) wrote the discussion, and approved the final manuscript. EB assessed risk of bias (with LA) wrote the introduction and approved the final manuscript. All authors contributed to the article and approved the submitted version.

Acknowledgments

The authors thank librarian Gøril Tvedten Jorem for assisting the literature search.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fspor.2022.1031004/full#supplementary-material

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frontiers | Frontiers in Sports and Active Living

TYPE Original Research
PUBLISHED 26 October 2022
DOI 10.3389/fspor.2022.857554

OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Physical Activity in the Prevention and Management of Disease, a section of the journal Frontiers in Sports and Active Living

RECEIVED 18 January 2022
ACCEPTED 12 September 2022
PUBLISHED 26 October 2022

CITATION
Connell H, Logan G, Somers C, Baker G, Broadfield S, Bunn C, Harper LD, Kelly P, McIntosh E, Pell JP, Puttnam J, Robson S, Gill JMR and Gray CM (2022) Development and optimisation of a multi-component workplace intervention to increase cycling for the Cycle Nation Project. *Front. Sports Act. Living* 4:857554.
doi: 10.3389/fspor.2022.857554

Development and optimisation of a multi-component workplace intervention to increase cycling for the Cycle Nation Project

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The Cycle Nation Project (CNP) aimed to develop, test the feasibility of and optimize a multi-component individual-/social-level workplace-based intervention to increase cycling among office staff at a multinational bank (HSBC UK). To do this, we first explored barriers to cycling in a nationally-representative survey of UK adults, then undertook focus groups with bank employees to understand any context-specific barriers and ways in which these might be overcome. These activities led to identification of 10 individual-level, two social-level, and five organizational-level modifiable factors, which were mapped to candidate intervention components previously identified in a scoping review of cycling initiatives. Interviews with HSBC UK managers then explored the practicality of implementing the candidate intervention components in bank offices. The resultant pilot CNP intervention included 32 core components across six intervention functions (education, persuasion, incentivisation, training, environmental restructuring, enablement). Participants received a loan bike for 12-weeks (or their own bike serviced), and a 9-week cycle training course (condensed to 6 weeks for those already confident in basic cycling skills), including interactive information sharing activities, behavior change techniques (e.g., weekly goal setting), bike maintenance training, practical off-road cycling skill games and on-road group rides. Sessions were delivered by trained bank staff members who were experienced cyclists. The CNP pilot intervention was delivered across three sites with 68 participants. It was completed in two sites (the third site was stopped due to COVID-19) and was feasible and acceptable to both women and men and across different ethnicities. In addition, the CNP intervention was successful (at least in the short term) in increasing cycling by 3 rides/week on average, and improving perceptions of safety, vitality, confidence, and motivation to cycle. Following minor modifications, the long-term effectiveness and cost-effectiveness of the CNP intervention should be tested in a full-scale randomized controlled trial.

KEYWORDS

cycling, workplace intervention, active travel, intervention development, co-design, evaluation

Introduction

Cycling is associated with several physical and mental health benefits, including lower risk of all-cause mortality (1–3), lower incidence of cardiovascular disease (3, 4), type 2 diabetes (5), stroke (6), hypertension (7), and breast and colon cancer (8), as well as, increased cardiorespiratory fitness (9), improved body composition (9), lower levels of stress, anxiety and depression (10), and improved wellbeing (11, 12) and cognitive function (13, 14). The largest health gains occur in the transition between not cycling, or cycling infrequently, to more regular cycling, rather than from regular cyclists further increasing their cycling volume (15). In addition, if cycling replaces motorized transport, it can reduce air pollution (16), carbon emissions (15) and congestion (17). The UK has low levels of cycling compared with several other European countries (18, 19) with only 11% of adults in England reporting cycling at least once a week (20). Nevertheless, there appears to be a latent demand for cycling, with surveys reporting that over half of UK adults would like to cycle more (21). Thus, with appropriate strategies, the potential to increase cycling in the UK, and to realize the multiple individual and public health, economic and societal benefits associated with this, is substantial.

The socio-ecological model suggests that interventions to promote cycling can be targeted at multiple levels including: (i) individual, (ii) social (including organizational), and (iii) built-environment (22, 23). A considerable body of evidence exists for the effectiveness of built-environment approaches to increasing cycling, but fewer studies have evaluated individual- and social-level behavioral initiatives, with mixed effectiveness to date (24). However, research in European countries with good cycling infrastructure has demonstrated that focusing solely on improving the built environment is not sufficient to maximize cycling participation (21, 25). Therefore, increasing cycling—which is a multifaceted behavior performed across multiple domains (commuting, utility, and leisure)—requires the range of barriers that prevent people from taking up and sustaining cycling to be addressed (26). At an individual level, barriers include lack of cycling skills and confidence (27, 28), feelings of physical discomfort (29), perceptions of effort (30) and lack of safety (31), and cost (32). At a social level, family, friends and work colleagues have also been shown to influence people's attitudes toward cycling (33).

The workplace is increasingly recognized as an important setting for delivery of health promotion interventions (34). Workplaces have the potential to encourage healthy behaviors—such as utility and leisure, as well as commuting, cycling—through adopting appropriate policies and promoting a supportive culture (35). In addition to being beneficial for the employee, workplace-based cycling interventions may provide benefits to the employer, including increased productivity (36) and reduced absenteeism (37). Whilst a number of workplace cycling initiatives have been trialed, many have focused on single components, such as cycle reward schemes (37), salary-sacrifice cycle purchase schemes (38), cycle challenges (39), or one-off cycle events (40). Few workplace initiatives have adopted an integrative approach, targeting both individual and social barriers to cycling over a consolidated period of time, which is likely to be necessary to maximize effectiveness given that most people report multiple barriers acting at different levels (41).

The aim of the Cycle Nation Project (CNP) was therefore to develop and pilot a multi-component individual-/social-level workplace-based intervention to increase cycling amongst people who cycle infrequently or not at all. In this paper we report the conceptualization and co-design of the CNP pilot intervention (Phase 1), and subsequent feasibility testing and optimization (Phase 2) using the 6SQuiD model (42) as a framework for intervention development.

Phase 1—Conceptualization and co-design

The CNP was set up as a collaboration between academics at the Universities of Glasgow and Edinburgh, and key stakeholders [British Cycling (a UK cycling governing body), and the multinational bank, HSBC UK] to increase cycling across the UK. The approach aimed to develop an intervention to increase cycling participation amongst staff at HSBC UK offices, which, if successful, could be rolled out more widely across other similar organizations nationally and internationally.

Phase 1 encompassed the first five steps of the 6SQuID model (42), as shown in Table 1. Initially, to build on existing evidence, further define the causes of problem (low levels of cycling) and identify which of these might be changed in our target population (6SQuID steps 1 and 2), we performed a secondary analysis of data on barriers and attitudes to

TABLE 1 An overview of the methods used to address the six steps in quality intervention development (6SQuID) in the Cycle Nation Project.

6SQuID step	Methods
1. Define and understand the problem and its causes.	• Secondary analysis of national survey data • Six focus groups with HSBC UK employees
2. Clarify which causal or contextual factors are malleable and have greatest scope for change.	• Six focus groups with HSBC UK employees (as above)
3. Identify how to bring about change: the change mechanism.	• Mapping exercise • Face-to-face interviews with five HSBC UK office managers • Co-design workshops with 10 HSBC UK staff
4. Identify how to deliver the change mechanism.	• Face-to-face interviews with five HSBC UK office managers (as above) • Co-design workshops with 10 HSBC UK staff (as above)
5. Test and refine on small scale.	• Face-to-face interviews with five HSBC UK office managers (as above) • Co-design workshops with 10 HSBC UK staff (as above) • Phase 2 feasibility study
6. Collect sufficient evidence of effectiveness to justify rigorous evaluation/implementation.	• Phase 2 feasibility study (as above)

cycling from a nationally-representative, cross-sectional survey of UK adults. We then conducted focus groups with HSBC UK employees to: first, understand the relative importance to our target population of the barriers identified by the UK-wide survey; second, explore any additional context-specific barriers; and third, identify ways in which the barriers might be overcome. The findings were mapped onto the results of an earlier CNP systematic scoping review of group and organizational initiatives to promote cycling (24) to identify candidate intervention components and the mechanisms of change (6SQuID Step 3). Finally, individual face-to-face interviews with HSBC UK office managers and co-design workshops with HSBC UK staff were used to finalize the pilot CNP intervention core components, Program Theory and delivery format (6SQuID Steps 3-5) for the Phase 2 feasibility study (6SQuID Step 6).

Ethical approval for Phase 1 data collection was obtained from the University of Glasgow College of Social Sciences Ethics Committee (Ref. 400170195). All participants provided written informed consent.

Defining the causes of the problem and scope for change

Secondary analysis of nationally-representative survey

In 2017, British Cycling commissioned a nationally-representative UK-wide survey of barriers and attitudes to cycling. The survey involved 5,000 respondents at four, quarterly timepoints between May 2017 and March 2018 (total $N = 20{,}000$) to account for potential seasonal variation in cycling. We conducted a descriptive secondary analysis of the survey data that focused on responses to two questions. The first, "What currently stops you from cycling or cycling more often?", was asked of a subset of 14,999 respondents who reported not cycling as much as they could. The second, "Why do you have no interest in cycling?", was asked of a subgroup of 2,347 respondents who reported they were not interested in either starting cycling or cycling more often. Respondents were stratified into: "Never Cyclists" (those who had never cycled or not cycled since childhood); "Lapsed Cyclists" (cycled in adulthood but not in the past year); "Occasional Cyclists" (cycled in the past year, but less frequently than once per month); "Regular Cyclists" (cycled between once per month and once per week); and "Frequent Cyclists" (cycled more than once per week).

The results are summarized in Table 2. We focused on responses from Never, Lapsed and Occasional Cyclists as representative of the CNP intervention target population (people who cycle infrequently or not at all). Amongst these groups, lack of perceived safety, lack of confidence riding on the roads and bad weather were the most highly cited barriers, reported by about half of respondents. Lack of time, particularly with respect to home, family and work commitments, was also a common barrier, particularly amongst Occasional Cyclists. Lack of knowledge of local places to cycle and unsuitable terrain were reported as barriers by about a quarter of respondents. Other barriers were less frequently mentioned, and interestingly, relatively few respondents reported cost as being important. Amongst the subgroup of respondents who did not want either to start cycling or to cycle more, the most frequently reported reasons were not liking cycling as a sport or preferring other sports, highlighting a perception of cycling as a sport rather than as an everyday activity. Concerns about the safety of cycling were also reported by this group.

Focus groups

Focus groups were then conducted at six HSBC UK workplaces (Manchester, London, York, Birmingham, Liverpool

TABLE 2 Responses to questions about barriers to cycling in a nationally-representative UK survey.

Question	What currently stops you from cycling or cycling more often? ($n = 14{,}999$ respondents reporting that they did not cycle as much as they possibly could)				
	Cycling category				
	Never cyclists ($n = 5{,}439$)	Lapsed cyclists ($n = 5{,}128$)	Occasional cyclists ($n = 2{,}766$)	Regular cyclists ($n = 914$)	Frequent cyclists ($n = 842$)
The cycling (on-road) infrastructure does not make me feel safe	52.8%	55.3%	45.6%	42.6%	34.9%
I don't feel confident riding my bike on roads	54.4%	54.2%	43.4%	35.5%	29.2%
Bad weather puts me off cycling as a hobby	46.2%	47.0%	51.7%	46.0%	35.3%
I do not have the time owing to home/family commitments	26.7%	28.4%	43.6%	39.5%	32.9%
I do not have the time owing to work commitments	21.3%	22.9%	41.9%	37.8%	33.9%
I don't know of any facilities where I can cycle	30.7%	27.4%	25.0%	21.9%	18.7%
The local terrain doesn't suit me	29.1%	28.0%	23.5%	19.9%	15.7%
Cycling requires too much faffing around	30.9%	21.1%	19.9%	14.0%	16.6%
I do not have the time owing to other leisure/social commitments	18.4%	19.4%	30.4%	25.7%	24.9%
Cycling is too expensive	23.8%	17.2%	14.3%	14.4%	14.4%
There are not enough cycling events in my area	17.2%	13.8%	18.4%	18.6%	17.9%

(Continued)

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TABLE 2 (Continued)

Question	Why do you have no interest in cycling? ($n = 2,347$ respondents reporting not being interested in either starting cycling or cycling more often)				
	Never cyclists ($n = 1,177$)	Lapsed cyclists ($n = 894$)	Occasional cyclists ($n = 166$)	Regular cyclists ($n = 43$)	Frequent cyclists ($n = 67$)
I am not interested in sport	41.4%	25.7%	21.1%	23.3%	17.9%
Cycling is not safe	22.2%	22.0%	14.5%	0.0%	6.0%
I prefer other sports	16.0%	22.7%	25.3%	14.0%	16.4%
Cyclists do not behave safely	15.6%	15.2%	7.2%	2.3%	3.0%
Cycling is too expensive	6.9%	5.9%	3.6%	2.3%	1.5%
I don't like cycling clothes	6.7%	5.6%	6.0%	16.3%	3.0%
There is too much doping in professional cycling	3.3%	3.7%	0.6%	7.0%	1.5%
Cycling excludes women	0.2%	0.5%	0.6%	0.0%	0.0%
I cycle already but I have no desire to cycle more often	0.1%	2.2%	29.5%	60.5%	61.2%
Other reason	19.1%	29.4%	5.4%	7.0%	9.0%
Don't know	10.8%	12.3%	18.1%	4.7%	11.9%

Percentages refer to those agreeing or agreeing strongly to the question on a five-point scale.

10.3389/fspor.2022.857554

and Edinburgh) between August and November 2018. The sites were selected to represent geographical diversity across the UK. Staff were sent an internal email asking those who had cycled less than once a month in the past year if they were interested in taking part. The focus groups (each 6–8 participants, mean $N = 7$) were conducted by HC, an experienced qualitative researcher, and lasted on average 77 min (range 63–90 min).

The discussions were digitally recorded and transcribed verbatim with participant consent. Anonymized transcripts were analyzed using a thematic framework approach (43) and NVivo12 software to organize the data. Two transcripts were read independently by three members of the research team with expertise in qualitative methods (HC, GL, CMG), who then met to agree a coding frame. The coding frame was applied to all transcripts by HC and GL, and 13 broad themes; "Time," "Safety," "Environment," "Effort," "Views toward bikes/e-bikes," "Other people," "Storage," "Security," "Infrastructure/facilities," "Education/training," "Cycle schemes," "Maintenance," and "Incentives" were identified. These were then explored in detail to identify 10 broad barriers and 22 associated specific factors limiting cycling among HSBC UK staff, displayed in Table 3. Similar to the survey, lack of time due to competing family and work commitments, and safety concerns emerged as important barriers (for women in particular); the latter stemmed from a lack of confidence about cycling on roads (including cycling in traffic) and perceptions of poor cycling infrastructure. Furthermore, in relation to effort, unsuitable terrain (i.e., hills and distance) was reported as discouraging people from cycling. The cost of cycling (not just the bike itself, but also the cost of associated equipment) appeared to be more important for focus group participants than survey respondents. Some also complained about lack of social support (including support/guidance from more experienced cyclists) and not having anywhere to store a bike at home (lack of space and/or living in a flat). Others described how a lack of workplace facilities (showers, lockers, bike storage) and not having a supportive workplace culture for cycling (including not being able to wear appropriate clothes for cycling) deterred them from commuting by bike. Some also felt they lacked the skills and experience needed to cycle safely from place to place and to maintain their bike in a road-worthy condition. Finally, despite HSBC UK participating in a subsidized bike purchase cycle-to-work scheme, many were unclear how to use this. They also reported finding local cycle-share schemes, designed to help people access affordable cycling, difficult to navigate.

Following discussion of the focus group findings, the CNP team (including the University researchers and British Cycling representatives) agreed on 17 (from the 22) specific factors that could potentially be modified within a group-based workplace intervention. These included 10 individual-level factors relating to lack of confidence, knowledge and skills, cost and effort (where it was agreed that e-bikes might overcome some of the issues related to hills and distance). Two social-level factors (namely having peers and mentors/role models to cycle with) were also addressable through a group-based intervention in the workplace. Finally, an additional five factors (professional dress code, access to spares/tools, and lack of bike storage, showers and lockers) were identified as being modifiable at the organizational level. A diagrammatic summary of all modifiable factors is provided in Figure 1.

Identifying the change mechanism

A full day workshop involving five university researchers and two British Cycling representatives was held to map the activities (action types) reported by the earlier CNP systematic scoping review (24) and focus group participants' suggestions of how to support people to cycle more (facilitators) against the modifiable factors. The results of this theoretical mapping exercise are provided in Supplementary Table 1. It identified 68 candidate intervention components relating to 26 action categories (groups of components sharing a similar function) across seven intervention functions (IF) from Michie et al.'s Behavior Change Wheel (BCW) (44). The action categories included: increasing knowledge/understanding of the benefits of cycling, cycling safety, route planning and how to cycle, and signposting to cycling organizations (IF—Education); individual and group counseling and travel diaries (IF—Persuasion); material (e.g., loan of bike) and financial (e.g., work cycle scheme, free bike servicing, and safety equipment) incentivisation, and gamification/challenges (e.g., goal setting and certificates) (IF—Incentivisation); training courses (IF—Training); secure bike storage and changing/maintenance facilities, cycling personnel, mass participation events, group cycling, workplace policies (including flexible dress code and working hours) (IF—Environmental restructuring); buddying (IF—Modeling); provision of bikes/ebikes, accessories and maintenance, and signposting to cycle share schemes (IF—Enablement).

Refining the pilot CNP intervention core components and delivery format

Telephone interviews with managers (all men) from five of the HSBC UK workplaces involved in the staff focus groups (Manchester, London, York, Birmingham, and Liverpool—no managers from Edinburgh were available for interview) then explored the practicality of implementing the CNP candidate intervention components within bank offices. The five interviews (mean duration 44 min, range 24–86 min) were conducted in January 2019 by GL and HC and audio recorded with participant consent. GL and HC listened to the audio recordings and took notes (including supporting extracts) to summarize the managers' views.

TABLE 3 Broad barriers and specific factors limiting cycling identified by HSBC UK staff focus group participants.

Broad barrier	Specific factor	Supporting extract
Lack of time	Family and/or work commitments	*I'd like to do more, but for me it's just lack of time. I don't get a minute to myself of a morning or of a night really. I couldn't structure it in… (Participant 4, M, Liverpool)*
Lack of perceived safety	Lack of confidence	*At the moment, I'm afraid on my bike. I'm not completely confident of the route in and out to work (Participant 2, F, Edinburgh)*
		…we don't know how to deal with icy footpaths, we don't know how to deal with crosswinds, we don't know how to deal with, you know. So, it's the actual physicality of being safe (Participant 2, F, Edinburgh)
	Poor environmental infrastructure	*We need to improve the infrastructure more than anything else… you'll get cycle paths and then all of a sudden, no cycle path. And you're just stuck in the middle of the road (Participant 3, M, Manchester)*
	Poor road surfaces	*[the] bike riding side just reminds me of potholes… I just don't think our roads are great (Participant 5, M, Liverpool)*
	Traffic	*…I'm afraid to stay on the road, because I'm afraid of the cars, the traffic, or I don't have confidence with traffic (Participant 2, F, Edinburgh)*
Effort	Hills	*It's quite a hilly country….I don't want to cycle up a hill. I want to cycle on a flat, serene ground (Participant 5, M, Manchester)*
	Distance	*…if I worked a lot closer to home, that would assist, cos then I wouldn't think about the taking the car. Even if I worked, like, five or six miles away, I could bike. But that's unlikely to be able to happen (Participant 2, F, York)*
Cost	Cost of bike	*"I've been talking about, with my wife, that we should get a bike, but they're quite expensive and, you know, you just… you know, kind of, postpone it and postpone it (Participant 6, M, Manchester)*
	Cost of equipment (e.g., helmet and clothing)	*There's quite a high barrier to entry if you want to buy a bike and not stand out like a sore thumb… because you spend at least a few hundred quid on a road bike and then you look at clips, shoes, lycra, gloves, helmet, jersey, two or three water bottles… It's a grand before… (Participant 3, M, Birmingham)*
Lack of social support	Work colleagues, friends, family not interested in cycling	*Me and my husband have got a bike and I've asked him loads of times, but he's just not bothered (Participant 2, F, Birmingham)*
		For me I mainly cycle at home, and the limiter for me would be friends, because none of my friends really do it (Participant 2, M, London)
	No cycling role model/mentor	*…if I had a buddy, that would teach me the etiquette, what to do when I'm coming across someone, you know… who's got right of way (Participant 2, F, Edinburgh)*
Lack of facilities at home	Practical and secure storage	*I live in a very small flat… I've got nowhere to keep a bike (Participant 3, F, London)*
		I'd have no space to put the bike away. Just… prams, there's kids' toys...the house is just one big nursery basically. I'd have no space (Participant 4, M, Liverpool)
Lack of facilities at work	Secure storage	*If you're going to encourage everyone to bike to work, say 20/25 people are all coming here on a bike, then there's nowhere near enough places to leave your bike (Participant 5, F, York)*
	Showers	*More facilities at work like showers. At the moment we've got two showers, one in the men's, one in the ladies'. And I think… they're not private (Participant 5, F, York)*
	Lockers	*…there's a massive waiting list for a locker (Participant 5, M, London)*
Lack of cycle friendly workplace culture	Professional dress code	*It would be odd to just have some people who dress down… the whole culture would have to change (Participant 7, F, London)*
		…and then I need to put my shirt in my bag and then that's going to be creased (Participant 1, M, York)
	Bike spares/tools (inner tube, pump etc.)	*That sounds good, actually… like a maintenance station that's at your workplace. So if there is anything that's to happen, to go wrong, then you know you could fix it, or there's spare whatever, in the building (Participant 1, F, Edinburgh)*
Lack of skills	Unsure how to cycle on the road	*….I knew how to ride a bike, but I didn't know how to do it safely on the roads… I'm used to getting to places by trains or buses or Ubers, but I've never actively gone out to gain that education on how to ride bikes on the roads. It's mainly the safety element for me (Participant 1, F, Birmingham)*

(Continued)

TABLE 3 (Continued)

Broad barrier	Specific factor	Supporting extract
	Lack of experience	*…some of these fears that we have it's probably because we never rode bikes on these busy* roads when we were kids. *(Participant 5, M, London)*
	Lack of bike maintenance skills	*…changing an inner tube, etc.…is something people would need to know (Participant 5, M, Liverpool)*
Lack of knowledge	Unsure which cycle routes are suitable/how to plan a route	*I'm in the center of the city, so how do I get from point A to point B, to a point of safety (Participant 3, F, Edinburgh)*
	Lack of knowledge about cycle schemes (e.g., cycle-to-work)	*...the cycle to work scheme. That's quite good, isn't it. Do HSBC do that? (Participant 4, M, York)*

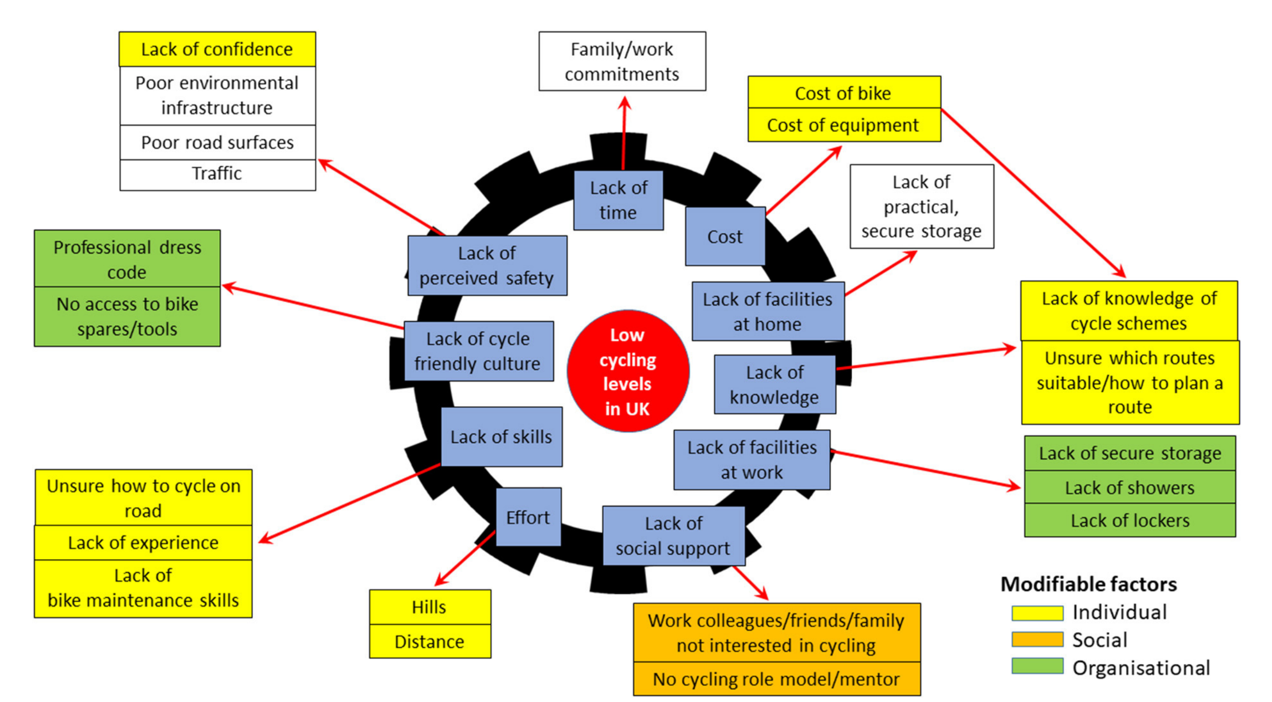

FIGURE 1
Barriers to cycling (shown in blue) and associated modifiable factors at individual, social and organizational levels.

All managers were confident there were suitable outdoor facilities at their offices for delivering practical components of the CNP intervention:

> *There's certainly space, absolutely, it's a huge branch with space to do that. I guess cost would come into it, but there is the facilities there, and they certainly could be extended.* Manager 2

They supported the idea of training staff volunteers who were enthusiastic cyclists to become Cycle Champions certified to deliver the CNP intervention. One noted that this sort of initiative aligned with current organizational policy within HSBC UK:

> *…we've got some people who have done ride leader courses. We're encouraging more of our staff to do that.* Manager 1

There was broad agreement that provision of bikes (including the option of ebikes) would be essential to encourage participation in the intervention:

> *I think the idea of a loan bike would be a really good idea and maybe a loan bike for a period of time of a week or a month or maybe longer. So, the people who haven't got those could give it a proper go...* Manager 3

However, there was little support for the introduction of a flexible dress-code. Managers felt this could be difficult to implement, particularly where staff were working in customer-facing roles:

> *I guess my view is I would be concerned about any item of clothing that can go through the wear and tear of cycling through the elements and still look smart and professional in a banking environment, that would be the challenge.* Manager 2

Although the adoption of a flexible working hours policy was not immediately dismissed, some managers felt in smaller branches there might be issues around implementation that would require careful negotiation:

> *. . . a lot of our branches are open at 8 a.m. and close at 6 p.m.... by arrangement... if one of my team said to me, I want to come in early and leave late... I want to cycle to work every day... I might be able to accommodate somewhere in-between, say for two days a week, you can do that...* Manager 4

The CNP research team (including representatives from British Cycling and HSBC UK) used the findings from the manager interviews to: first, confirm 32 core components relating to 16 action categories across six BCW intervention functions for inclusion in the pilot CNP intervention (summarized in Table 4); and second, finalize the CNP Program Theory. As Figure 2 shows, as well as drawing on the evidence from the theoretical mapping exercise, staff focus groups and manager interviews, the CNP Program Theory was also informed by Self-Determination Theory (45), which suggests that people are more likely to initiate and sustain a new behavior (such as cycling) if their motivation to perform a behavior is internally (rather than externally) regulated.

The core components and CNP Program Theory were then used to develop the delivery protocol and participant handbook for a practical 9-week cycling intervention and an associated 2-day Cycle Champion training course. These resources drew on existing British Cycling materials, where appropriate. A CNP app was also developed to support self-monitoring and goal setting for both cycling and bike maintenance.

In the final stage of intervention development, GL and HC conducted two co-design workshops with staff at HSBC UK offices in London ($N = 5$ staff) and York ($N = 4$ staff) to refine the intervention for delivery in the Phase 2 feasibility study. Detailed field notes were taken, and, together with audio-recordings of each workshop, were written up electronically to summarize participants' views.

One important concern raised during both workshops was that early off-road practical skills sessions might be too basic for some people. Some participants suggested that two levels of the intervention (one basic, one more advanced) might be needed to cater for different levels of confidence and experience:

> *I think a one size fits all is not where you need to go with it... I don't need to see how to break, or turn a corner, I can do all of that stuff.* Workshop Participant 4, Female, York

> *Maybe what you need is two different programmes, one for beginners...* Workshop Participant 5, Female, London

Overall, the core components were viewed favorably, and staff were particularly positive about the prospect of taking part in the CNP intervention alongside other co-workers with similar cycling skills and experience:

> *The social content, being able to do it in a group, you're not alone... having the support of your peers, it's a strong incentive in itself.* Workshop Participant 4, Female, London

The final CNP intervention that was piloted in the Phase 2 feasibility study comprised two versions: a 9-week Foundation Course and a condensed 6-week Intermediate Course for participants who were already confident in basic cycling skills. The sessions combined interactive information sharing (including bike and personal safety, benefits of cycling, route planning), behavior change techniques (46) (including goal setting and review, self-monitoring of cycling, barrier identification and problem solving, social support, overcoming setbacks), bike maintenance training, and practical off-road cycling skill games and on-road group rides.

Phase 2—Feasibility testing and optimization

In Phase 2, we conducted a mixed-methods before-and-after study to assess the feasibility (including recruitment, adherence and practical aspects of delivery), acceptability and potential effectiveness of the CNP pilot intervention [6SQuiD Step 6 (42)]. Three large HSBC UK offices were selected to take part in the feasibility study. These were chosen as having an adequate pool of potential participants, access to areas suitable for delivery of the off-road practical activities and adequate storage to allow participants to bring their bikes to work for intervention sessions, and to represent the geographical diversity of the UK, and The first delivery of the CNP pilot intervention took place at a central London office between August 6th and October 8th, 2019; the second at an office in a business park on the outskirts of Edinburgh between October 1st and November 27th, 2019; and the third at an office in a business park outside Southampton starting February 12th, 2020 (the COVID-19 pandemic halted this delivery in March 2020).

TABLE 4 Cycle Nation Program intervention core components identified following theoretical mapping and manager interviews.

Intervention function	Action category – CNP core components
Education	**Increasing knowledge or understanding of benefits of cycling**
Increasing knowledge or understanding	*–Information on time-saving benefits of cycling (SR)*
	–Information on cost benefits of cycling (SR)
	–Information on time taken to cycle route (e.g., in app) (FG)
	Increasing knowledge or understanding of cycling safety
	–Information on cycling safely (SR, FG)
	–Information on cycle étiquette (FG)
	–Acting out travel scenarios (SR)
	Route planning/personal and individualized travel planning
	–Information on accessibility and local routes (SR, FG)
	–Travel and safe-route maps (SR, FG)
	–Digital cycling apps (SR, FG)
	–Cycling website (SR, FG)
	Practical or instrumental information
	–General practical "Everything you need to know about cycling" information (SR)
	Signposting to cycling resources/organizations
	–Cycling-related contacts (SR)
Persuasion	**Group counseling**
Communication to induce +ve/–ve feelings or stimulate action	*–Group counseling (including barrier identification and problem solving) to increase cycling (SR)*
Incentivisation	**Material**
Creating expectation of award	*–Bikes for attending sessions (SR)*
	Financial
	*–Subsidy, salary sacrifice, tax free loan for buying bike and equipment (SR, FG)**
	–Cycling-related gifts
	–Free bike service for taking part
	Gamification/challenges
	–Goal setting and personal challenges (SR)
	–Awards and certificates (SR)
	–Active games (SR)
Training	**Training courses and sessions**
Imparting skills	*–Cycle skills, proficiency and safety training and courses (SR, FG)*
	–e-Bike skills and proficiency training and courses (SR, FG)
	–Maintenance skills courses (FG)
	–Independent skills practice (SR)
Environmental restructuring	**Group cycling**
Changing the social environment	*–Led group bike rides (SR,FG)*
	Workplace or organizational policies
	–Training internal staff to become certified cycling instructor (SR)
Enablement	**Provision of bike accessories**
Increasing means/reducing barriers to increase capability or opportunity	*–Safety equipment (helmets, lights, reflective strips) (SR, FG)*
	Provision of eBikes
	–Loan of eBike to use during intervention/eBike trial before purchase (SR, FG)
	Provision of bikes
	–Short term hire or lease of bike during intervention (SR, FG)
	–Information on how to access shared cycle schemes (FG)
	Provision of bike maintenance
	–General bike maintenance (SR, FG)
	–Bike repairs (SR, FG)

SR, Scoping Review; FG, Focus Groups.
*Existing HSBC UK cycle-to-work scheme.

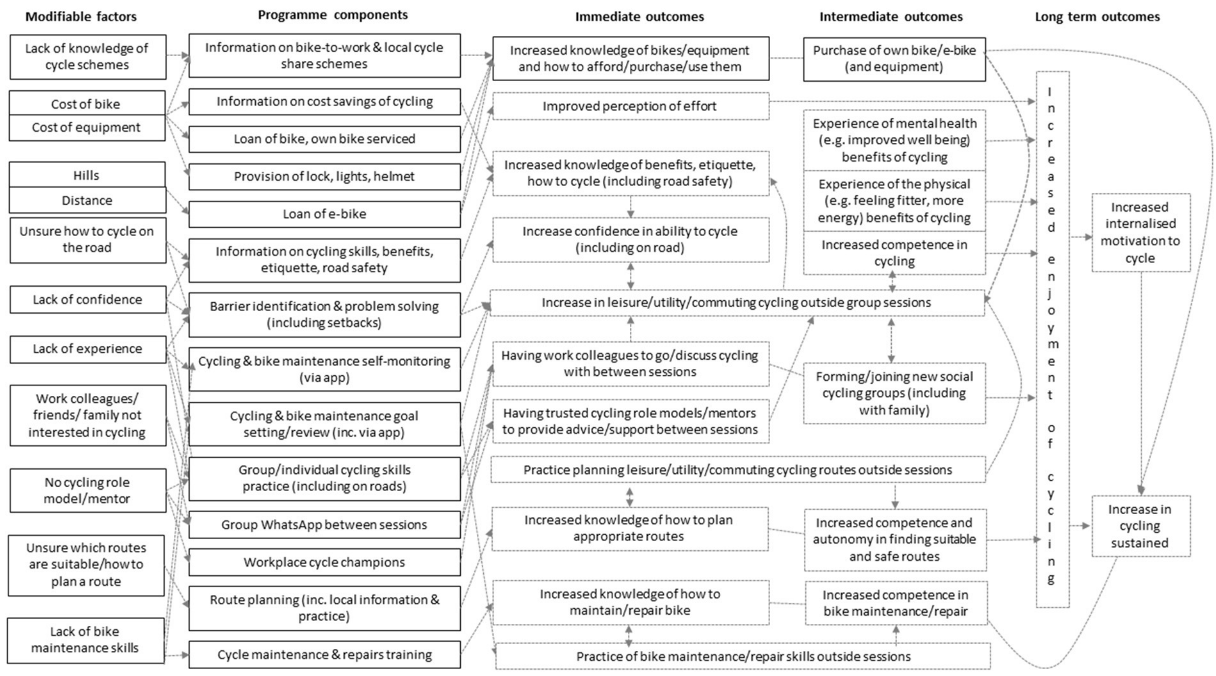

FIGURE 2
The Cycle Nation Project program theory.

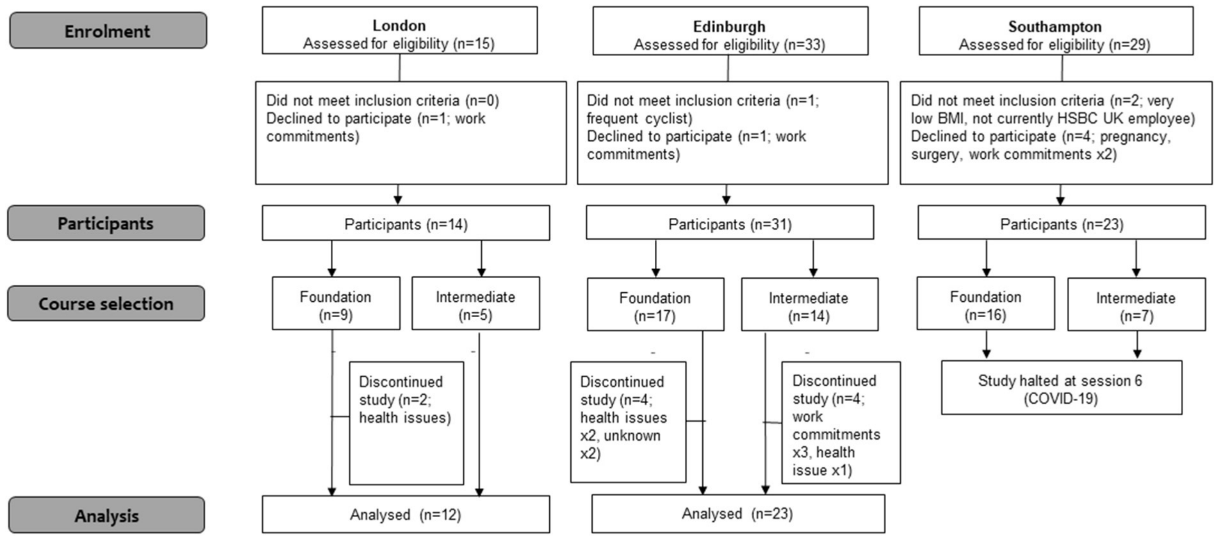

FIGURE 3
Flow of participants through the Cycle Nation Project feasibilty study.

Methods

Recruitment

We aimed to recruit 5–10 Cycle Champions and 20–30 participants at each office from staff members aged ≥18 years. Cycle Champions were recruited *via* an email from a central HSBC UK manager and were eligible if they were self-identified, competent cyclists. All underwent a 2-day CNP training course run at each of the three offices by a qualified British Cycling trainer and a University of Glasgow researcher

(GL). The course was designed to be highly interactive and to provide experiential learning of how to deliver the CNP core components using the intervention delivery protocol, including: facilitating group discussions; encouraging the use of behavior change techniques; delivering practical training including bike maintenance and cycling skills; and leading group rides. Champions also underwent 1-day First Aid training certification.

Participants were recruited *via* email, office posters, face-to-face interactions with Cycle Champions (all sites) and an information session (London only). Staff were eligible if they were able to ride a bike but were currently cycling infrequently (less than once a month) or not at all. To confirm their eligibility, those who expressed interest in the study, were emailed a questionnaire asking, "Over the past 12 months, on how many occasions have you cycled?" and the Physical Activity Readiness Questionnaire [PAR-Q+ (47)] to confirm they did not have any contraindications to exercise. Once screened, participants were asked if they wanted to loan a bike for the duration of the intervention [and which type (e.g., ebike, hybrid, and folding) and model they would prefer] or have their own bike serviced.

Cycle nation project pilot intervention delivery

CNP sessions were delivered in the early evening immediately after work at London and Edinburgh sites, and during the lunch break at Southampton. The first three Foundation sessions and the first Intermediate session were delivered in traffic-free outdoor locations near each office. These were identified by Cycle Champions and included an unused basketball court near the London office and empty staff car parks in Edinburgh and Southampton. Once participants progressed to the on-road sessions, Cycle Champions identified low-traffic roads close to the offices for group rides. Although initially it was envisaged that the Foundation and Intermediate groups would meet separately, in practice these tended to be merged into a single session in later weeks.

Two large national bicycle shops with partnership agreements with British Cycling and HSBC UK were identified to supply loan bikes for 12 weeks (to cover the duration of the intervention and some additional weeks to allow participants to transition to buying their own bikes) or to provide servicing for those opting to use their own bike. Loan bikes were purchased by HSBC UK from the partnering bike shops for the Edinburgh and London deliveries and then pooled into a bike fleet for Southampton. Loan options included hybrid, road, folding and ebikes to suit a range of usage requirements. All participants also received helmets, locks and rear lights for taking part (participants at Edinburgh also received front lights to allow them to cycle safely during the late autumn/early winter evening sessions).

Data collection

To assess participant recruitment, the numbers of HSBC UK staff expressing an interest in CNP intervention, assessed for eligibility, and completing screening and baseline measures were recorded by the University of Glasgow research team. To assess intervention attendance and completion (adherence), Cycle Champions were asked to return session attendance registers *via* email to the University of Glasgow research team each week. In London, Cycle Champions asked any participants who missed sessions for their reasons for non-attendance, whereas in Edinburgh and Southampton, participants were telephoned by a researcher if absent from two consecutive sessions. Participants were judged to have completed the intervention if they attended at least two-thirds of available sessions. In-depth audio-recorded telephone interviews were conducted by HC with five of the 18 participants who did not complete the intervention in London and Edinburgh to explore reasons for non-attendance (mean duration 16 min; range 13–18 min).

To assess acceptability and the practical aspects of delivery, three face-to-face focus group discussions or paired interviews were held with participants who completed the intervention in London (one focus group with seven participants) and Edinburgh (one focus group with four participants and one paired interview) in the week after the intervention ended. Participants were invited by email to take part in focus groups/interviews held in their office during working hours. All focus groups/interviews were conducted by GL and lasted on average 58 min (range 50–64 min). Post-intervention telephone interviews with Cycle Champions were conducted by HC in London ($n = 3$) and Edinburgh ($n = 5$); they lasted on average 28 min (range 15–35 min). Finally, GL conducted three additional telephone interviews with Southampton participants to explore acceptability of the CNP app, which, due to delays during its development, only became available for the Southampton delivery (mean duration 10 min; range 5–14 min).

An interview schedule was used to guide focus group discussions/interviews around participants' views of the CNP pilot intervention, what was useful/not useful and what could be improved for future deliveries. Cycle Champions were also asked about the training, delivery materials and any adaptations they made during intervention delivery. The Southampton interviews focused on participants' views and experiences of using CNP app and its specific features, including self-monitoring and goal setting. All focus groups and interviews were audio recorded with participant consent.

To assess practical aspects of delivery and inform intervention optimization, selected delivery sessions ($N = 25$, including Foundation-only, Intermediate-only and Joint sessions) were observed across the three sites (London $n = 10$, Edinburgh $n = 10$, Southampton $n = 5$) by members of the research team (GL, HC, CMG). After each session, written summaries were completed electronically following an observation proforma focusing on how/if key components were delivered and any operational issues (e.g., timing, access to loaned bikes/servicing, and bike storage). Full details of which sessions were observed are provided in Supplementary Table 2.

To explore potential effectiveness, 1 week prior to starting and within 3 weeks of the end of the intervention, participants completed online questionnaires including self-reported frequency of total, leisure, commuting and utility (e.g., going to the shops) cycling. Other measures included perceptions of cycling and walking safety (48), motorized transport use, self-esteem [Rosenberg Self-Esteem Scale (49)], wellbeing [Warwick-Edinburgh Mental Wellbeing Scale, WEMWBS (50)], self-reported vitality [modified Subjective Vitality Scale, SVS (51)], and motivation for cycling [modified Behavioral Regulation in Exercise Questionnaire, BREQ-2 (52)].

At baseline, self-reported characteristics (age, gender, ethnicity, and bike ownership) and whether participants wanted to loan a bike/have their own bike serviced were also recorded, and researchers trained in standardized protocols visited each office to collect objective weight and height measurements. Weight (kg) was assessed using electronic scales (Tanita HD 352, Middlesex, UK) with participants removing shoes and emptying their pockets prior to measurement. Height (cm) was assessed using a portable stadiometer (Seca Leicester, Chino, CA, USA) with shoes removed. Each participant's body mass index (BMI) was calculated as weight (kg)/height $(m)^2$. Finally, to ensure participant safety during the intervention, resting blood pressure was measured using a digital blood pressure monitor (Omron HEM-705CP, Milton Keynes, UK). Three participants with elevated blood pressure (systolic $\geq$140 mmHg and/or diastolic $\geq$90 mmHg) were encouraged to consult their GP before commencing the intervention, but were not excluded from taking part. At follow-up, participants were also asked to rate different aspects of the CNP pilot intervention, both specific content and overall, using a 5-point Likert scale where 1 = "Strongly Disagree" and 5 = "Strongly Agree".

Analysis

Focus groups and interview audio recordings were transcribed verbatim. Anonymized transcripts were analyzed using a thematic framework approach (43) and NVivo12 software to organize the data. GL and HC read all transcripts to agree a coding framework comprising six themes based on the feasibility study research questions: i.e., feasibility, acceptability, potential effectiveness and optimization (a description of each theme is provided in Supplementary Table 3). They then applied the coding framework to all transcripts, double coding one interview and one focus group to ensure it was applied consistently. The framework was also applied to the electronic observation proformas by GL.

Recruitment, attendance and completion data were compiled in Excel spreadsheets to calculate summary descriptive data (numbers and percentages). We defined completion of the program as attendance of at least two-thirds of sessions. Questionnaire and measurement data were analyzed using SPSS version 22 (IBM Corporation, Armonk, NY). Participant baseline characteristics were reported using descriptive means and frequencies. Potential effectiveness was explored using paired t-tests to assess changes in outcomes between baseline and post-program. Significance was set at $p \leq 0.05$.

Ethical approval

Ethical approval for Phase 2 was obtained from the University of Glasgow College of Medical, Veterinary and Life Sciences Ethics Committee (Ref. 200180138). All participants provided written informed consent.

Results

Feasibility—Recruitment and adherence

Four Cycle Champions (all men) were recruited at the London office. Ten (8 men, 2 women) were recruited at the Edinburgh office, and eight (6 men, 2 women) were recruited at Southampton. Two Cycle Champions withdrew following training: one due to illness (London) and one due to issues with session delivery times (Edinburgh). As shown in Figure 3 and Table 5, a total of 68 HSBC UK office staff took part in the CNP pilot intervention across the three sites (London $n = 14$, Edinburgh $n = 31$, Southampton $n = 23$). Participants in were aged on average 39.8 (SD $\pm$ 10.0) years, and 54.4% were men. Over 60% were either overweight or obese, and over three quarters reported their ethnicity as white. More participants selected the Foundation course than the Intermediate course, and fewer than half already owned a bike.

Overall, participants attended 62.5% of sessions, and 60.0% (27/45) completed the intervention. London participants attended 61.5% of sessions, and 71.4% (10/14) completed the intervention (as defined by attending at least two thirds of available sessions). Attendance was similarly good in Edinburgh (63.4%) and extremely high in Southampton (98.1%) up to the point the program was suspended (after week 5) due to COVID-19. Full detail of attendance is provided in Supplementary Table 4. The clear structure of the program was valued by participants and motivated many to keep attending:

I knew what was coming up in every session, and that was helpful [...] having a structured weekly detailed idea of what was going on that kept me going back. Foundation Participant 1, Female, Edinburgh

However, despite the good attendance in Edinburgh, completion (54.8%, 17/31) was lower than in London. Exit interviews suggested that this may have been due to winter weather and low light during evening sessions toward the end of the program. In addition, adherence tended to be poorer

TABLE 5 Participant baseline characteristics ($n = 68$).

Participant characteristics	Mean ± SD or *n* (%)
Age (years)	39.8 ± 10.0
Gender (*n*, %)	
Male	37 (54.4)
Female	31 (45.6)
BMI (kg/m^2)	27.1 ± 5.9
BMI category (*n*, %)*	
Underweight	1 (1.5)
Normal	26 (38.2)
Overweight	23 (33.8)
Obese	18 (26.5)
Ethnicity (*n*, %)	
White	52 (76.5)
Asian/British Asian	12 (17.6)
Other	4 (5.9)
Course choice (*n*, %)	
Foundation	42 (61.8)
Intermediate	26 (38.2)
Bicycle ownership (*n*, %)	32 (47.1)

*BMI categories: underweight (<18.5 kg/m^2), normal (≥18.5–<25 kg/m^2), overweight (≥25–<30 kg/m^2), obese (≥30 kg/m^2).

among Intermediate participants in Edinburgh, leading one local Cycle Champion to question whether running courses at two different levels was worthwhile (particularly given the logistical considerations of doing so):

The intermediate course to me pitched at the wrong level, it's too basic for...there's no need for it. Cycle Champion 3, Male, Edinburgh.

Feasibility—practical aspects of delivery

Of the 68 participants at baseline, 82.4% (56, London $n = 10$, Edinburgh $n = 25$, and Southampton $n = 21$) opted to loan a bike to take part in the intervention (this included some who already owned a bike). Over half of participants (53.6%) opted for hybrid bikes, 19.6% chose a road bike, 17.6% chose an e-bike and 8.9% selected a folding bike. Full detail of bike loans is provided in Supplementary Table 5.

It was originally envisaged that participants would store their bikes at home and bring them into work for program sessions. However, many participants left their loan bikes at their office for convenience:

> *… there was a big faff 'cause I was having to put it…I couldn't even fit it in my car 'cause I've got a Fiesta, so I was having to get my husband to take it and drop it and then pick it up and stuff like that. But then I think in a way for me again having the storage here for the first few weeks, it meant that I didn't have to take it home straightaway*. Foundation Participant 5, Female, Edinburgh

One benefit of having their bikes on site was that participants were able to access them between sessions to build a social cycling network (e.g., through additional lunchtime group rides). This led to additional demands on workplace storage, which were successfully accommodated at London and Southampton. However, session observations revealed that limited storage facilities at Edinburgh meant that participants' bikes were stored in a locked room, which was initially only accessible to Cycle Champions. Participants were therefore unable to use their bikes for group rides between sessions.

Acceptability

All Cycle Champions felt the delivery manual and 2-day training course gave them confidence to deliver the CNP intervention (which for many of them was a new experience):

I've never delivered training like that before. But actually, it felt quite natural, the way it happened, and everyone was really nice and listened to what you were saying. It was good. Cycle Champion 3, Male, London

The cycle champions valued the group delivery format for creating a facilitative environment where participants felt comfortable and able to support each other in gaining cycling skills and confidence:

> The most effective component *was definitely the group exercises and having people of equal ability or slightly different ability but encouraging each other. As a group it worked quite well with the dynamics where there was lots of discussion between the participants, and they were encouraging each other to do things or to take part*. Cycle Champion 3, Male, London

The participants were also extremely positive about most aspects of the CNP intervention. Of the 32 participants from London and Edinburgh who completed follow-up questions about the acceptability of the CNP pilot intervention components and overall, 87.5% reported increased confidence in cycling at the end of the program and over 80% said they enjoyed it (84.4% Agree/Strongly Agree). Almost all felt the sessions were well delivered (96.9%) and the information in the handbook was clear (93.8%)—although only 53.1% reported using the handbook regularly. The opportunity to loan a bike (95.8%) [and the range of loan bikes available [87.5%]] was appreciated by those who did so ($n = 24$ respondents), with the majority (75.0%) indicating the 12-week loan period was sufficient. However, for those opting to use their own bikes ($n = 8$ respondents), 37.7% were not entirely satisfied with the quality of servicing; this largely reflects the fact that participants in London did not get their bike serviced due to issues with the local bike provider. Most participants felt the duration of the sessions (90.6%) and overall length of the program (84.4%) were appropriate and liked the balance between discussion and riding time (81.3%). Many activities within the sessions were also rated highly, including those associated with bike maintenance (71.9–87.5% Agree/Strongly Agree) and the practical components (75.0–90.6%). However, discussion of behavior change techniques—goal setting (64.5%), involving others (65.6%), and relapse prevention (56.3%)—was generally less popular. Further details of participants' responses are provided in Supplementary Table 6.

Some focus group participants further described how the CNP intervention had helped them rediscover the enjoyment of cycling, and how the skills and knowledge acquired during the initial off-road sessions allowed them to feel comfortable when moving to on-road cycling, both with the group and independently:

> *I surprised myself with how confident I felt on the roads when we started to go on the roads as well because I just was really scared about that. But, no, that's been great.* Foundation Participant 6, Female, Edinburgh

Importantly, despite the Foundation and Intermediate groups in London and Edinburgh being merged from Week 5 onwards, this woman did not feel the wider range of abilities undermined the supportive culture that had been established in the early weeks:

> *I think even on the group rides and stuff like that, although there was a lot of different abilities, and I would say I would probably be maybe the least... you know, like, had the least ability, but it* [merging the groups] *worked out fine. Everybody, kind of, sort of, checked in on everyone else and... you know, there wasn't really that, kind of, you know, you can't do this or we won't be able to do this on this route or whatever, kind of thing.* Foundation Participant 6, Female, Edinburgh

Participants also appreciated the fact that staff from within their office were trained as Cycle Champions to deliver the program. As one man reflected, this provided him with inspiration and motivation to cycle more:

> *I think a lot of it for me was getting a, quote unquote, cyclist expertise on it [...] for me it was good to see an actual person who does it semi-seriously and does it on a very, very regular basis to see their actual official way of doing things and to instil some procedure. You could tell that they were there, they wanted to share their knowledge, they were keen to share it and to instil that same passion that they had with other people.* Intermediate Participant 2, Male, Edinburgh

Potential effectiveness

The evidence presented above suggests the CNP pilot intervention was feasible and acceptable to Cycle Champions and participants. As Table 6 shows, the intervention also succeeded in helping participants increase their cycling by 3.0 rides ($p < 0.001$) and 43.1 min per week ($p = 0.02$), with more participants reporting increases in leisure (57.1%) and utility (40.0%) cycling, than in commuting (31.4%). Table 7 further demonstrates improvement in perceptions of cycling and walking safety, and increases in levels of vitality. Finally, internally regulated types of motivation, including identified, integrated and intrinsic motivation, all increased during the intervention.

Intervention optimization

Session observations revealed that the intervention was well-delivered overall, but that some activities needed streamlined to allow the content to be delivered within the time allocated to each session. However, one recurring issue observed across multiple sessions was poor delivery of the goal setting (SMART Target) activity:

> *More emphasis on SMART targets/practical targets needed. Did they achieve their individual targets etc. If they are not discussed, then participants may not feel the need to do them regularly.* Observation Foundation Session 5, London

The Cycle Champions themselves admitted to being less comfortable about delivering the behavior change components than the practical cycling components. Some suggested that the format of the goal setting activity, where participants were asked to write their personal SMART goals in their handbook each week, was a barrier to its delivery:

> *...the SMART objectives that we set individuals every week, they were very difficult to police and manage. Again, because there wasn't any evidence of people bringing their handbooks week on week and we weren't obviously checking that what they said they were doing, they were doing.* Cycle Champion 1, Male, London

Despite participants being reminded to bring their handbooks to each session, it was soon evident that this was impractical:

> *... there is no way in the dark in the night and outside on our bikes, you know, some people just turning up in their coats and their jackets, just turning up, there is nowhere for them to keep their book.* Cycle Champion 2, Male, Edinburgh

Therefore, following discussion with the Cycle Champions at Edinburgh, goal setting was adapted during later sessions to

TABLE 6 Post-intervention changes in cycling and motorized transport (Edinburgh and London sites, all $n = 35$).

	Pre-intervention (mean ± SD)	Post-intervention (mean ± SD)	Change (mean ± SD)	*p*-value
Total cycling (rides/week)	1.2 ± 2.5	4.2 ± 4.1	3.0 ± 4.6	**<0.001**
(min/week)	12.7 ± 31.4	55.9 ± 92.6	43.1 ± 100.9	**0.02**
Utility cycling* (days/week)	0.4 ± 0.9	1.1 ± 1.4	0.8 ± 1.6	**<0.001**
Commuting cycling (rides**/week)	0.6 ± 1.4	1.7 ± 2.7	1.1 ± 3.0	**0.04**
Leisure cycling (rides/week)	0.2 ± 0.5	1.4 ± 1.5	1.2 ± 1.6	**<0.001**
Motorized transport use (min/week)	405 ± 464	255 ± 180	150 ± 442	**0.05**
Participants reporting increased rides per week for different types of cycling, and overall, post-intervention (*n*, %)				
Overall		22 (62.9)		
Utility*		14 (40.0)		
Commuting		11 (31.4)		
Leisure		20 (57.1)		

*Utility cycling includes shopping, running errands, school run, etc.
**Commuting rides are defined as one way of a return journey.
Bold values represent statistical significance ($p < 0.05$).

TABLE 7 Post intervention changes in perceptions of the environment for safe cycling and walking, wellbeing, self-esteem, vitality, and motivation (Edinburgh and London sites).

	Participants (*n*)	Pre-intervention (mean ± SD)	Post-intervention (mean ± SD)	Change (mean ± SD)	*p*-value
Perceptions of the safety of cycling and walking	35	43.9 ± 7.1	47.7 ± 6.3	3.8 ± 6.2	**<0.001**
Vitality	34*	17.6 ± 4.8	19.4 ± 5.3	1.8 ± 5.1	**0.05**
Self-esteem	34*	26.3 ± 2.2	26.4 ± 1.5	0.1 ± 2.6	0.74
Wellbeing	34*	50.0 ± 6.6	50.7 ± 7.8	0.7 ± 5.9	0.49
Motivation					
Amotivation	34*	1.30 ± 0.41	1.27 ± 0.46	−0.03 ± 0.47	0.72
External regulation	34*	1.15 ± 0.30	1.25 ± 0.51	0.11 ± 0.42	0.14
Introjected regulation	34*	1.74 ± 0.91	2.49 ± 0.87	0.75 ± 1.03	**<0.001**
Identified regulation	34*	3.44 ± 0.97	3.82 ± 0.80	0.38 ± 0.88	**0.02**
Integrated regulation	34*	1.68 ± 0.84	2.32 ± 1.12	0.65 ± 1.01	**<0.001**
Intrinsic motivation	34*	3.50 ± 1.08	4.18 ± 0.77	0.68 ± 1.11	**<0.001**

*One incomplete questionnaire.
Perceptions of the environment for safe walking and cycling, range 13–65; Wellbeing: Warwick-Edinburgh Mental Wellbeing Scale, range 14–70; Self-esteem: Rosenberg Scale, ranging 10–40; Vitality: Subjective Vitality Scale, range 4–28; Motivation: Behavioral Regulation in Exercise Questionnaire, each domain range 1–5.
Bold categories represent outcomes from the different questionnaires stated in the legend.

become a verbal activity, with a dedicated log provided to allow the Champions to record participants' individual cycling goals each week.

It had originally been envisaged that the SMART goal setting and self-monitoring of cycling would be also be supported by the CNP app, but delays in development of the self-monitoring component meant the app only became available for the Southampton delivery. However, Southampton participants remained unclear about the app's role in the intervention, with some appearing to think that it was simply to help them with route planning:

> *The reason I haven't used it [the app] was because I was in the longer [Foundation] group… and it was only two weeks ago that we were all going to be going out on the road and therefore using this [the app] to ride…* (Interviewer: Did you have a look at any of the other functionality on it?) No. Female Participant 3, Foundation, Southampton

Taken as a whole, therefore, the feasibility study suggests that the CNP pilot intervention was well-implemented in the HSBC UK setting and that only a few minor changes were needed to optimize its delivery. These included further development of a simplified goal setting activity and, in order to improve practicality of delivery, combining different abilities to offer a single 9-week intervention to all participants, as shown in Table 8.

Discussion

Increasing participation in cycling requires addressing multiple barriers together (24). The CNP intervention was therefore conceived as an integrative program addressing different barriers to cycling for people who cycle infrequently. Combining multidisciplinary academic expertise with practical and contextual experience from British Cycling and HSBC UK stakeholders (including as members of the research team), as well as the target end-users, allowed us to co-develop a workplace-based intervention that was appropriate for delivery in the study setting (bank offices), succeeded in recruiting local delivery facilitators (Cycle Champions) and participants, was well-received and increased cycling participation in the short-term.

Our key innovation was to use an evidence-based approach guided by the rigorous step-by-step 6SQuID intervention development framework (42), theoretical accounts of behavior change [the Behavior Change Wheel (44) and Self-Determination Theory (45)] and evidence-based behavior change techniques (46), and move beyond single-component workplace cycling interventions (36, 39, 40, 53) to design a multi-component individual-/social-level intervention tailored to address the specific barriers to cycling for our target population (employees of a multi-national bank). These barriers were broadly similar to those observed in previous research, and included lack of cycling skills and confidence (27, 28), lack of safety (31) and social support (33), perceptions of effort (30), and cost (32). Importantly, the CNP pilot intervention attracted people from minority ethnic groups and almost as many women as men, indicating its widespread appeal. This universality means the CNP intervention is likely to be transferrable to other large employers, as well as potentially to other types of organizations, such as local authorities and community groups.

Relatively few workplace-based studies have evaluated the impact of cycling interventions on cycling behavior. Examples include an education-based intervention to increase active commuting in three large workplaces in the UK, which was effective at increasing walking but not cycling (54), and a social and individualized marketing campaign in 68 health service employees in Australia, which reported a non-significant increase (37–45%) in the proportion of staff using active commuting at 12 months (55). The mean increase in total cycling in the current study of 3.0 rides or 43.1 min per week compares favorably with these studies. Importantly, involvement in the CNP pilot intervention, as well as increasing perceptions of safety, also increased feelings of vitality, confidence and the more internalized forms of regulation that are associated with sustained behavior change (45).

Our findings also compare well with community-based cycling interventions. For example, a cycling proficiency program for adults in Australia resulted in a non-significant 10 min per week increase in cycling 2 months after the course (28); an adult cycle training program in the UK increased the proportion of participants cycling at least once a week from 40 to 61% at 3-month follow-up (56); and a 12-week group-based cycling intervention for lower-income adults in Milwaukee, USA, which included on-road education and group rides, cycle safety information and provision of bikes for participants, significantly increased the proportion of participants reporting utility cycling (by 7.2%) and cycling for fun (by 42.9%) at least twice per week from baseline to post-intervention (57). It is of note that the most successful of these previous studies (57), like CNP, also used a multi-component intervention approach.

Although regular cycling to replace other forms of transport is likely to be cost-saving (58, 59), the initial outlay of several hundred pounds to try out an activity that people are not sure is "for them" may be daunting. Therefore, the 12-week loan of a bike to support participation in CNP and transition to bike ownership was a central feature of the pilot intervention that most participants took advantage of, including some who already had their own bikes. However, although we envisaged participants would keep their loan bikes at home and bring them to work for CNP sessions (thus promoting cycling commuting), many chose to leave their loan bikes at work. As a result, although the feasibility study did demonstrate a significant increase in cycling commuting, the contribution of commuting to the total increase in cycling was less than utility and leisure cycling. In future, therefore replacing the relatively costly individual loan bikes with a fleet of shared workplace bikes (with priority given to CNP participants during the intervention) could be considered as a more cost-efficient, sustainable way of promoting a positive workplace cycling culture. Such an arrangement would also alleviate any additional pressure on workplace bike storage (as observed in Edinburgh) due to participants leaving loan bikes at work during the intervention.

Other issues identified during the feasibility study included some sessions being impacted by bad weather and poor light at Edinburgh, due to the fact that the program delivery began in autumn. At Southampton (where the program began in early February) sessions were run at lunchtime rather than in the evening. However, whilst this overcame the problem of poor light, daytime sessions and cycling practice may still be impacted by bad weather at this time of year. Therefore, Spring to early Autumn is likely to be the optimal period for intervention delivery.

In addition, although the Champions were confident about delivering the practical components of the CNP intervention, they were less comfortable about delivering the behavior change techniques, such as SMART goal setting. The fact

TABLE 8 Final CNP intervention: Summary of key activities for each weekly session.

Week	Discussion and behavior change techniques	Bike maintenance	Practical
1	What to wear and carry when cycling Reasons for cycling more Introduction to cycling goals In your own time activities (M-check) Introduction to cycle-to-work scheme WhatsApp social support	Introduction to the M-check	Fitting your helmet Adjusting saddle height Foot position Off-road: Starting and stopping effectively (Inc. get-ready position and braking), Slow bike race
2	Goal and activity review Introduction to SMART Targets for cycling Introduction to self-monitoring for cycling In your own time activities (dropped chain)	M-check second arm Fixing a dropped chain	Using gears Off-road: Multiple gear race
3	Cycling SMART Target review and setting Introduction to barriers In your own time activities (locking bike)	M-check final arms	Locking your bike Off-road: Cornering, Slalom game and team relay race
4	Cycling SMART Target review and setting, and activity In your own time activities (front wheel lift) review	Pumping up tire	Off-road: Avoiding obstacles, Front wheel lift, Cycling skills game
5	Cycling SMART Target review and setting Your rights on the road Involving others In your own time activities (road positioning) Reminder of cycle-to-work scheme		Off-road: Signaling, Emergency stops On-road: Road positioning, Quiet junctions
6	Cycling SMART Target review and setting Barriers and problem solving In your own time activities (traffic lights)	Chain lubrication	On-road: Traffic lights, Filtering, Roundabouts
7	Cycling SMART Target review and setting In your own time activities (changing inner tube)	Changing an inner tube (including on the rear wheel)	
8	Cycling SMART Target review and setting Overcoming setbacks In your own time activities (planning a route)		Route planning using Google Maps On-road: Group ride following planned route
9	Cycling SMART Target review Overcoming future barriers Ongoing SMART Targets Ongoing social support Graduation certificates		On-road: Group ride

that participants gave low ratings to many of the behavior change components may also reflect the sub-optimal delivery of these activities. Furthermore, although the CNP app was designed to help participants monitor their cycling, the app was not available for testing until the Southampton delivery. As interviews suggested participants did not use the app for its intended purpose, it will not be used in the optimized version of the program. Further refinement (including some co-development with Cycle Champions and users) may therefore be required to optimize engagement with the behavior change techniques during the CNP intervention.

Finally, the additional complexity and Cycle Champion commitment required to deliver two versions of the program meant that Foundation and Intermediate group sessions were often merged. Therefore, despite the demand for the two different levels in the program development workshops, a more streamlined single-level, 9-week foundation-level program appears to be more feasible to deliver in practice.

This study had a number of strengths. Most importantly, co-development of the intervention with stakeholders, including staff and managers from across HSBC UK, and inclusion of bank and British Cycling representatives on the research team ensured the pilot intervention could be delivered within the practical opportunities and constraints of the organizational context. In addition, selection of different offices to represent geographical diversity across the UK, supports the wider implementation of the CNP intervention necessary for a future full-scale randomized controlled trial and post-research roll out. Finally, in two of the three feasibility offices, women staff members volunteered to be Cycle Champions. Nevertheless, more could be done to promote the Cycle Champion role to experienced women cyclists to provide a range of cycling role models within each office whose lifestyles and personal commitments are relatable to all participants. The main limitations were lack of a control group and the suspension of the study in March 2020 due to COVID-19, meaning that no participants from the third delivery site contributed to post-program data collection, and that we were unable to conduct longer-term follow-up. Nevertheless, the fact that the forms of motivational regulation associated with behavior change maintenance increased significantly is promising in relation to the intervention's potential to support sustained behavior change.

Conclusion

The CNP intervention was co-developed iteratively with key stakeholders and end-users drawing on experiential and theoretical evidence. This resulted in an intervention that was successful (at least in the short term) in increasing cycling and improving perceptions of safety, vitality, confidence and motivation to cycle. In addition, the intervention was feasible when delivered to staff within the offices of a UK-based multinational bank, and acceptable to both women and men, and across different ethnicities. Given that the barriers to cycling highlighted by bank employees were similar to those identified in the general population, the CNP intervention has potential to be delivered through different organizations, including other large employers and local authorities as part of their wellbeing and active travel initiatives. The long-term effectiveness and cost-effectiveness of this approach should be tested in a full-scale randomized controlled trial.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by University of Glasgow College of Social Sciences Ethics Committee (Ref. 400170195) and University of Glasgow College of Medical, Veterinary and Life Sciences Ethics Committee (Ref. 200180138). The patients/participants provided their written informed consent to participate in this study.

Author contributions

CG, JG, PK, GB, and EM contributed to conception and design of the study. GL, CG, HC, and JG designed the intervention delivery materials, were involved in data collection, and wrote the first draft of the manuscript. GL and CG supported the Cycle Champion training. GL, HC, JG, CB, and CG undertook data analysis. All authors contributed to intervention development, contributed to manuscript revision, read, and approved the submitted version.

Funding

This work was supported by a Research Grant from British Cycling and HSBC UK.

Acknowledgments

We would like to thank Allan Clare from HSBC UK for overseeing the Cycle Nation Project; Robbie George, and Allison Coles from British Cycling for additional work in development of the Cycle Nation Program intervention and delivery materials, and Will Henwood and Diana Farrell from British Cycling for support in training the Cycle Champions to deliver the intervention. We are also grateful to the HSBC UK staff and managers who participated in the intervention development focus groups, interviews, and workshops; the Cycle Champions who delivered the intervention; and the HSBC UK staff members who participated in the feasibility study.

Conflict of interest

The nature of the co-design of the Cycle Nation Project intervention meant that the funders, British Cycling and HSBC UK, were intimately involved in the design and delivery of the intervention, and representatives from both organizations are authors on the paper. All data analysis was performed by researchers at the University of Glasgow without input from British Cycling or HSBC UK. Authors SB and JP were employed by British Cycling, and authors SR and LH are employees of HSBC UK.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fspor.2022.857554/full#supplementary-material

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frontiers | Frontiers in Sports and Active Living

TYPE Original Research
PUBLISHED 04 January 2023
DOI 10.3389/fspor.2022.1067127

OPEN ACCESS

EDITED BY
Gareth Stratton,
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SPECIALTY SECTION
This article was submitted to Physical Activity in the Prevention and Management of Disease, a section of the journal Frontiers in Sports and Active Living

RECEIVED 11 October 2022
ACCEPTED 21 November 2022
PUBLISHED 04 January 2023

CITATION
Niven A, Ainge JA, Allison M, Gorely T, Kelly P, Ozakinci G, Ryde GC, Tomaz SA, Warne S, Whiteford V and Greenwood C (2023) Building partnerships: A case study of physical activity researchers and practitioners collaborating to build evidence to inform the delivery of a workplace step count challenge.
Front. Sports Act. Living 4:1067127.
doi: 10.3389/fspor.2022.1067127

Building partnerships: A case study of physical activity researchers and practitioners collaborating to build evidence to inform the delivery of a workplace step count challenge

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Background: Walking is an integral part of Scotland's National Physical Activity Strategy, and the charity Paths for All's Workplace Step Count Challenge is a flagship programme within this strategy to promote physical activity. Effectively promoting physical activity requires collaborative engagement between stakeholders. However, there is limited guidance on how to do this. The aim of this case study is to share an example of a partnership between Paths for All and researchers to inform the development and delivery of the Workplace Step Count Challenge.
Method: An overview of the partnership, example activities, reflections on opportunities and challenges, and suggestions for future partnership working are considered.
Results: The partnership has evolved and strengthened over time through building trust. Many of the research activities provide an evidence base for the intervention. This work is mutually beneficial providing support for the work of the organisation, and opportunities for researchers to undertake "real world" research, leading to formal outputs and funding. The "real world" nature is challenging to integrate the most robust research designs. Recommendations for developing future partnerships were identified.
Conclusion: Promoting physical activity effectively requires partnership working, and this paper provides insight into how such partnerships can work to inform future collaborations.

KEYWORDS
worksite, evaluation, intervention, Scotland, collaboration

Introduction

Physical activity has well-established physical and mental health benefits (1–3). However, large proportions of the population across the world are insufficiently physically active to reap these benefits (4, 5). Active transport (including walking, cycling and wheeling) and workplace settings have been identified as two of eight global investments that work to enhance physical activity behaviour (6). Indeed, evidence indicates that workplace interventions can be effective in increasing physical activity (7), and targeting walking is a promising strategy (8). Workplace "challenges" incorporating activity trackers to count steps are common initiatives to promote employee physical activity through increased walking, including active travel. One such challenge is Paths for All's Workplace Step Count Challenge (9), which is a flagship programme within Scotland's National Walking Strategy.

Scotland's National Walking Strategy (10) was launched with a vision to create "A Scotland where everyone benefits from walking as part of their everyday journeys, enjoys walking in the outdoors, and where places are well designed to encourage walking." (p. 4). Consistent with global recommendations to support the optimal implementation of such policies (6), this strategy is operationalised in a wide-ranging action plan (11) working with partners across a range of sectors. The action plan highlights the importance of research to develop the evidence base for walking in Scotland, and to support the implementation of the strategy. The success of the action plan will depend on the development of effective cross-sector partnerships, such as collaborations between researchers and practitioners, who plan and deliver walking initiatives like the Workplace Step Count Challenge.

Researcher-Practitioner partnerships

Partnerships between researchers and practitioners have been increasingly called for by funders, government agencies, policy makers (12), and physical activity advocates (6). Across different disciplines and geographical locations, these partnerships have been given different names (e.g., integrated knowledge translation, knowledge transfer and exchange, research-practice partnerships) (13). Nevertheless, they are all based on the assumption that collaboration between researchers and practitioners/policy makers/other research users will "enable and enhance both the use of research and increase the amount of research relevant to end users" (12, p. 2). Indeed, these partnerships have been shown to have mutual benefits for both researchers and practitioners. For example, the collaborations may bring together different perspectives and expectations, which can lead to a broader understanding of needs and contextual influences, the identification and use of appropriate research methods for a context, and support routes to dissemination, and change of practice. Further, it has been suggested that the users of research benefit through increased awareness of relevant research, reflection on their own activities from different perspectives, and enhanced skills (13). Additionally, researchers benefit through a more nuanced understanding of the real world environment, the development of research questions with real world applicability, and through conversations about the interpretation and meaning of findings as they relate to real world situations (13). Given these mutual benefits, the research itself has greater potential for impact.

Nystom et al. (2018) (12) identified three main strategies to build or enhance research partnerships which are distinguished by who is driving the relationship, and these may change over time. In push strategies the relationship is driven by the researchers, which contrasts with pull strategies that are driven by the needs and demands of research users (14). The third strategy, linkage and exchange, is co-production of applied research useful for both parties (15).

Within physical activity research, this third strategy is reflected in Estabrooks and colleagues (16) proposal for collaborative working between researchers, practice professionals and decision makers to maximise the public health potential of physical activity interventions. Similar to others, they argue that the development of a mutual understanding of the value of different types of evidence and an acknowledgement of the unique knowledge, skills, and experiences that different collaborators bring to a project, mean that practitioners can act more readily on the best available evidence. Estabrooks et al. go on to describe an Integrated Research-Practice Partnership Practice Model (IRPPPM), which is based on an "iterative process used to co-produce research-based and practice-relevant evidence" (16, p. 4). Fundamental to this process is an emphasis on collaboration between practitioners, decision makers and researchers, and practicality with a move away from "push" strategies for evidence-based interventions, which may meet with resistance.

Research exploring research-practice partnerships has typically focused on the outcomes, and there has been less focus on the activities that characterise the partnerships. For example, there have been calls for researchers to capture and report on the nature of partnership activities; who is involved in what?; and how does it function? (13, 17). There are some examples reflecting on these collaborations in health care, educational, and community participatory research, but there are limited examples within the physical activity domain (e.g., 16, 18). Therefore, the overall aim of this paper is to illustrate as an example the development and strengthening of a partnership between the organisation Paths for All and the local research community to work collaboratively in building the best available evidence to inform the development and delivery of the workplace Step Count Challenge. The specific objectives are to share examples of partnership research activities, highlight the opportunities and challenges of undertaking research in a "real world" setting, and reflect on what we have learned that may be transferable to other settings and partnerships.

Setting the context: Paths for All and Workplace Step Count Challenge

Paths for All (PFA) is a Scottish charity whose vision is for a happier, healthier Scotland where physical activity improves quality of life and wellbeing for all. PFA's aim is to significantly increase the number of people who choose to walk for leisure or travel, to create better environments for walking, wheeling and cycling, and to influence policy at all levels [e.g., through the development of/contribution to policy documents including The National Walking Strategy (10)] to have an increased focus on physical activity. PFA receives Scottish Government funding to carry out this work.

PFA's Step Count Challenge (SCC) (9) is a flagship programme of the National Walking Strategy for promoting walking as an important part of the working day. The SCC was launched in 2011 to support workplaces to encourage staff to move more in-and-around the working day, and was designed to complement Public Health Scotland's Healthy Working Lives Award (19). The SCC is an online team-based walking challenge that has evolved over the last ten years to enhance the participant experience, and functionality of the interface. PFA has worked with users at each stage to make improvements based on feedback and delivered pilot challenges with stakeholders to test and review changes before launching.

In the 2021 delivery, participants registered on the SCC website in teams of five and paid £30 per team to participate. During the challenge, participants recorded their activity through a personal online dashboard; this activity can include walking, cycling, wheeling, running, swimming and yoga, and participants can also manually convert additional activities to steps. Activity data is added manually from participants own activity monitor, or by synchronizing with a selection of apps (Strava, Google Fit and Fitbit). Based on their recorded activity, participants are set tailored step-goals that increase as the challenge progresses. Participants can track and monitor their activity data and view leader boards that show how their total team step-count compares to others nationally. PFA provides update emails, competitions, prize draws, and blog posts on a range of topics.

The challenge runs twice a year, with an eight-week spring challenge and shorter four-week autumn challenge. It is open to workplaces from all sectors and they can register any number of teams. Workplaces can also set up bespoke challenges for their workplace at any time, with the workplace taking on the role of providing updates to participants during the challenge. In recent years the key messages of the SCC have focused on supporting participants to be active during the working day (e.g., through active meetings, taking regular desk breaks, etc.), promoting the mental health benefits of walking and being outdoors, and connecting with teammates either in person, or virtually.

Since 2011, PFA has delivered 19 national challenges and 78 bespoke challenges (introduced in 2016). The spring challenge generally attracts around 4,000 participants and the autumn challenge 2,000 participants. In financial year 2020/21 there were over 10,000 participations in SCC. With Covid-19 and the move to homeworking, there has been an increase in demand for bespoke challenges over the winter and spring of 2020/21 as workplaces look for ways to support staff whilst they are working remotely, and the challenge is seen as a tool to accomplish this.

Researcher-practitioner partnership on the Workplace Step Count Challenge

The partnership includes PFA staff and researchers based at five Scottish higher education institutions, including the Universities of Edinburgh, Glasgow, the Highlands and Islands, St Andrews, and Stirling, often working collaboratively. The initial partnership was established more than ten years ago, and has evolved to include additional institutions. Collectively this partnership has included a number of research projects focused on the SCC. **Table 1** provides an overview and synthesis of example research studies undertaken or ongoing as part of the partnership. The table illustrates the main research question, methods adopted, summary findings, study type, and outputs. These research studies have been undertaken both in response to requests from PFA and proposals from the universities to PFA, and were all approved by respective institutional ethical committees.

It is notable that a common theme across the studies has been to evaluate the effectiveness of the SCC on different outcomes. Studies have focused on documenting changes in physical activity (including steps) and also other health (i.e., cognitive, mental, physical), and work-related outcomes. More recent research has focused on developing a more nuanced understanding regarding for whom the SCC is effective (e.g., studies 3 & 6). Research activities are undertaken by established researchers, and also by undergraduate, postgraduate and doctoral level researchers, employing both quantitative and qualitative methods. A range of outputs have been produced, including both academic (e.g., peer-reviewed articles, conference presentations) and more external facing materials (e.g., blog posts, infographics), all detailed in

TABLE 1 Example research studies undertaken by the partnership.

Study focus	Method	Summary findings	Study type	Outputs
1. The impact of COVID-adapted SCC on mental well-being	Mixed-methods (quantitative questionnaires pre and post and qualitative interviews)	Enhanced well-being through: being outside and connecting with nature; it provided a distraction; mindfulness; social interaction	MSc student project	PFA blog—(20)
2. Evaluate the effect of 8-week SCC on physical activity behaviour and motivation using validated measures	Pre-post questionnaire design (within participant design)	Small changes in weekly walking, including walking for transport and leisure, but not at work. There were no significant changes in the other PA domains, with the exception of a reported decrease in sitting behaviour. Participants became more confident in walking, and were more autonomously motivated	Researcher project (internal funding)	Report to PFA (21), Infographic (see **Figure 1**), and video with PFA to communicate the findings to a wider audience (22). Peer review publication on motivation data (23).
3. Realist evaluation of SCC: How does a workplace walking programme produce its effects	Realist methodology: programme theory building using interviews and realist review, case studies to refine.	The process of "step counting in a workplace group" is a balance between personal goals and group dynamics. High levels of physical activity are generated from having fun, participating in a competition, and challenging oneself to do more. In other contexts, goal focus and group pressure can generate stress and/or drop out.	PhD student project (external funding ESRC SGSSS)	PhD Thesis (24) PFA podcast (25) and blogs (e.g., 26)
4. Evaluate the effect of 8-week SCC on changes in step-count across four years of delivery using routinely collected data	Quantitative analysis of routinely collected SCC data	Across the four years there was a largely consistent increase in step counts at each week compared with week 1. By week 8, participants had increased their steps by on average 906 steps per day	Researcher-led project (across 3 institutions) (unfunded)	Peer-reviewed publication (27). PFA news item (28)
5. What are the psychological determinants and consequences of participation in SCC?	Qualitative interviews	Main motives: incorporating more physical activity into their lives, and improving their fitness. Perceived benefits: weight loss, enhanced muscle tone, feelings of vigour, dedicated time to enjoy nature either by themselves or with others, the opportunity to be with own thoughts.	MSc project	Forthcoming
6. Multidisciplinary approach to quantifying the physical and mental health benefits of participating in SCC	Quantitative online survey at multiple time points Experimental studies	Ongoing analyses are examining links between physical and mental health with SCC participation. Forthcoming research to consider the link between SCC participation and cognitive function	PhD student project (external funding ESRC SGSSS)	Forthcoming
7. Evaluating the beneficial effects of the 4-week SCC on work-related outcomes, and highlighting challenges of "real world" research	Quantitative pre, week 1 and post SCC questionnaire	Preliminary data suggest positive changes in step, stress and productivity	Initially UGT project, then further developed (unfunded)	(29)

Table 1. This collective research effort is building the evidence for the beneficial effects of the SCC.

The opportunities from the researcher-practitioner partnership

From the perspective of PFA there have been a number of opportunities and benefits from the evolving research-practice partnership. As part of ongoing monitoring and evaluation for reporting to funders and to support ongoing improvements and efficiencies to the SCC experience, PFA collects a range of data and feedback from participants. Working with the universities in this partnership has created human capacity to explore in greater depth the experiences and outcomes of SCC participants. These activities have contributed to a deeper understanding of how the SCC works and for whom, including insight into participant's motivation and barriers, and team dynamics. These insights have directly led to improvements around the SCC platform, communications, messaging and design. Researchers have also provided informal assistance to test platform changes. Furthermore, researchers have contributed to blogs providing a different voice for SCC participants to encounter. Other less obvious benefits that PFA have noted include (1) the advocacy and awareness raising that occurs through academic presentations, posters, publications and networking; and, (2) the research partnership helping to demonstrate the impact of PFA's work thus supporting the case for future funding and resource. Finally, PFA view the partnership as a gateway to opportunities for further research collaborations to support their broader work. For example, researchers within this partnership have brought together other research colleagues to support a proposal for work with young people.

For researchers the opportunities from this collaboration are multiple. As illustrated in our examples, there is a mutually beneficial opportunity from this partnership to facilitate UGT, PGT and PhD student projects that can address and build evidence for areas of practice identified by PFA. Students benefit greatly from working on a "real world" project, and although for UGT and PGT the scale of work is unlikely to lead to a peer reviewed publication, in addition to completing their studies, students are typically supported to create an output that is accessible to a more lay audience. The experience of working with practitioners early on in their training also provides valuable opportunities for networking and skill development for establishing professional relationships. Importantly, outputs produced as part of these projects provide PFA with useful materials to share with funders and participants. Larger scale PhD and staff projects have the potential to lead to peer-reviewed publications, and the opportunity to collect data with PFA is of considerable benefit to researchers in undertaking this key aspect of their jobs. In addition to peer-reviewed publications, working with PFA and their communications experts has resulted in scientific communication outputs that are more effective in disseminating the findings more widely (see **Table 1**, and **Figure 1** for example). Such outputs are important in facilitating the impact of the research findings, which is increasingly recognised as a key indicator of research effectiveness (30).

As is evident throughout our descriptions of research, although some research is unfunded we have also been successful in securing both internal and external funding to support our collaborations. Having an enduring relationship with Paths for All, and their support in engaging with our research activities is certainly advantageous in applying for research funding. This funding enables us to dedicate further time to support the activities of the partnership, and ultimately produce outputs that are optimally useful to PFA. In such projects, more formal collaborative agreements between the institutions and PFA are implemented to address financial and legal requirements.

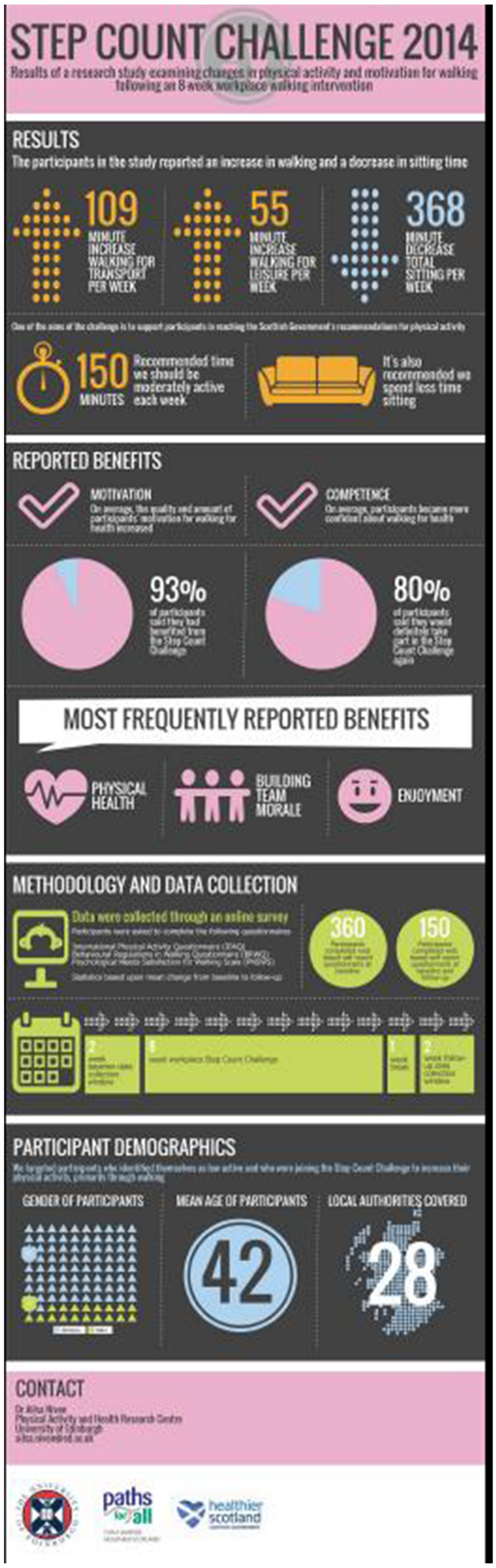

FIGURE 1
Example infographic reporting of research findings.

A final opportunity that as a collective we wanted to document, is that working together is rewarding. We do work truly pragmatically and collaboratively to find solutions to make the research happen. For example, during COVID-19 PFA supported an extension to their online portal to accommodate PhD data collection that facilitated the process in a seamless way. As researchers, we also benefit from working cross-institutionally, sharing discipline and methodological expertise around a common interest. This collaboration facilitates sharing of learning, avoidance of duplication, identification of gaps in knowledge, and working collectively to address challenges.

The challenges of the researcher-practitioner partnership

For PFA the main challenges of the partnership relate to ensuring that the participants are informed about why the research is being undertaken, and that the research activities are easy to engage in without additional burden.

The main challenges identified by researchers reflect more the challenges in undertaking research in the "real world", rather than necessarily the operationalising of the partnership. As Ryde et al. (29) also outline, challenges of collecting workplace outcomes during the SCC included low initial recruitment rates, poor compliance to data collection and lack of true baseline. For example, across our studies recruitment of participants has been challenging with a relatively small proportion of SCC participants choosing to take part in the research. In studies 2 and 7 listed in **Table 1**, recruitment rates were 10% and 12%, respectively. These challenges may in part be due to the inclusion of robust research measures, which can add participant burden. Participant attrition is a further challenge, when aiming to collect data over time. This leads to the problem of incomplete data sets due to instances of missing data points. Researchers then have to decide whether to use statistical methods to impute data from the sample or analyse only those participants who provided data for all time points. Although these recruitment and attrition challenges do occur and are common issues in real-world data collection, it is notable that working with PFA has been important to achieve even these levels of participation. For example, PFA support recruitment through endorsement, integrating data collection into existing systems, communications, and incentivising participation through the provision of "spot" prizes.

A further challenge that has limited the conclusions that can be drawn from studies, has been the absence of a true "baseline" in the online recording of steps by participants engaging in the SCC (27, 29). Typically, the first reported data has been from week 1, which may be elevated by initial enthusiasm, and mask the true effect of the SCC. Recommendations have been made to Paths for All about integrating research more effectively into real-world interventions, such as including a true baseline as part of the intervention itself and not just for research purposes, enhancing routinely collected data to include additional outcomes, and to automatically transfer this routine data (with relevant permissions) to reduce participant burden (29). However, this should not be to the detriment of the delivery of the intervention itself, where the primary objective is to increase physical activity.

An additional challenge, relates to the reliability and validity of the assessment of step counts. In all of the studies listed in **Table 1**, the researchers have relied on participants reporting their steps as assessed by their own device. Although commonly used "fitness trackers" are becoming increasingly sophisticated and robust (31), the research would be strengthened by being able to standardize measurement across participants. However, the resource and time required to do that is not always available, and can impact participant recruitment.

Ultimately, scaffolding the most robust research design around an ongoing programme is very difficult. For example, due to ethical, logistical and financial issues it is rarely possible to recruit a control arm to the study where characteristics of the individuals could be matched (e.g., age, gender, physical activity levels) to enhance the internal validity of the study. Therefore, from a perspective informed by a positivist bio-medical model, the research quality is compromised. However, as demonstrated by Allison (24), realist methodology (32, 33) offered the possibility to develop, refine and test a programme theory for the Step Count Challenge. Such theory has provided insights into how the SCC works, for whom, in what context, and why. Having this refined programme theory has helped clarify how and why this programme works and offers a new opportunity for others to test all or some of these theories, using a positivist bio-medical model.

Reflections, next steps, recommendations, and conclusion

Paths for All has worked with a range of researchers and academics for 10 years focusing on the SCC. The early phases of this collaboration were very much driven by individual researchers approaching PFA with ideas for research ("push" strategies); however, over time the relationship has become much more one of linkage and exchange, with questions and needs being identified through discussions with PFA and linking individual research teams together. This natural evolution reflects the different stages of research partnerships identified in the literature (12). This shift was at least partially driven by the perceived utility of the early work to help PFA gain a deeper understanding of the benefits of the SCC works.

We hope that this paper highlights the benefits of researchers and practitioners working together in partnership to undertake research that will address pertinent issues, and impact on practice. In preparing this paper, we have individually reflected on "why we do it" (i.e., work collaboratively). Whilst there are extrinsic benefits in terms of producing outputs, funding and evidence of impact, a key theme evident in our reflections, related to more intrinsic drivers. Specifically, the collaboration is fun and enjoyable, where as a collective we have a level of mutual respect for all that each partner brings to the collaboration, including students, researchers and PFA staff. This level of respect and trust has taken time to develop. We work hard to ensure open and regular communication during projects, and identify and articulate clear expectations that explicitly accommodate the needs of all parties. We then work hard to deliver on those outcomes, and as researchers ensure we "close the loop" and provide our partner with useful outputs.

As we move forward, we now plan to build on and formalise the collaborative partnership to work together to generate, evaluate and translate relevant evidence. This group will seek to enhance synergy and coherence in the way evidence informs the SCC. At the time of writing we are developing our Statement of Purpose (e.g., who, why, when, what), and have plans to enhance the visibility of the partnership through a web-presence to highlight our work, and to make sure the partnership is inclusive of other interested researchers. Such a forum will also support PFA's desire to effectively coordinate the different projects and ensure there is equity and transparency in the allocation of resources and opportunities.

Based on our reflections on the partnership and the opportunities and challenges we have encountered, we have identified some key recommendations that may help others who are developing new partnerships. Firstly, try not to force the partnership, and be mindful that it will take time (i.e., years not months) to establish trusting relationships. Secondly, aim to have clear roles and expectations within the partnership. Again, it will likely take time for expectations between partners to align, and be realistic as two different sectors come together. Thirdly, be prepared to compromise. For example, for researchers, it will rarely be possible to implement a highly controlled or randomised research design. For practitioners, research is rarely a quick process with rigorous processes required prior to, during, and after data collection. Finally, be mindful that the partnership should be mutually beneficial, and work together to ensure that each partner's needs are met. For example, for practitioners ensure that time is built into project planning to allow incorporation of research, and for researchers make sure to "close the loop" and deliver on promised feedback to practitioners and stakeholders.

To conclude, it has been recognised that collaborative partnerships are needed to effectively promote physical activity (6), and this paper has contributed to the literature by providing a specific example of how a research-practitioner partnership can work in the area of workplace physical activity. The paper has addressed a recognised gap in this area by focusing on who is involved in the partnership, and how it functions, rather than a sole focus on the outcomes of the research (13, 17). We hope that these insights, reflections and recommendations can support other researchers and practitioners in building fruitful collaborations that can enhance the relevance and impact of research activities.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author/s.

Author contributions

All authors conceived the manuscript. AN led the writing, with contributions from all of the authors. All authors contributed to the article and approved the submitted version.

Funding

Although the writing of this paper was unfunded, the research detailed in this paper has been funded by a number of sources. MA and SW have both received ESRC SGSSS PhD Collaborative studentships, where additional funding has been provided by Paths for All. AN has been funded by an University of Edinburgh CAHSS Knowledge Exchange grant. For the purpose of open access, the author has applied a Creative Commons Attribution (CC BY) licence to any Author Accepted Manuscript version arising from this submission.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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frontiers | Frontiers in Sports and Active Living

TYPE Original Research
PUBLISHED 01 March 2023
DOI 10.3389/fspor.2023.1125636

OPEN ACCESS

EDITED BY
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SPECIALTY SECTION
This article was submitted to Physical Activity in the Prevention and Management of Disease, a section of the journal Frontiers in Sports and Active Living

RECEIVED 16 December 2022
ACCEPTED 10 February 2023
PUBLISHED 01 March 2023

CITATION
Power D, Lambe B and Murphy N (2023) A critical analysis of walking policy in Ireland and its contribution to both national and international development goals.
Front. Sports Act. Living 5:1125636.
doi: 10.3389/fspor.2023.1125636

A critical analysis of walking policy in Ireland and its contribution to both national and international development goals

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Introduction: Increasing population levels of walking holds benefits for public and planetary health. While individual level interventions to promote walking have been shown to be efficacious, upstream interventions such as policies harness the greatest potential for impact at the population level. However, little is known about the nature and presence of walking policy in Ireland and the extent to which it aligns to national and global goals. This paper aims to provide an overview of local and national walking policy in Ireland and to understand the potential of Irish walking policy to contribute to national and global targets.

Methods: This study used multiple methods to provide a critical overview of walking policy. Firstly, a six-phase process was employed to conduct a content analysis of local and national walking policy in Ireland. Secondly, conceptual linkage exercises were conducted to assess the contribution of walking, and national walking policy in Ireland, to Ireland's National Strategic Outcomes and the United Nations Sustainable Development Goals.

Results: Overall, half ($n = 13$) of the counties in the Republic of Ireland were found to have no local level walking policies. Results from the content analysis suggest that counties which had walking specific local level policies ($n = 2$) were outdated by almost two decades. Walking was identified to hold the potential to contribute to over half ($n = 6$) of Ireland's National Strategic Outcomes, and over half ($n = 7$) of the United Nations Sustainable Development Goals. Ireland's only national level walking specific policy, the Get Ireland Walking Strategy and Action Plan 2017–2020, was identified to potentially contribute to four of Ireland's National Strategic Outcomes and three United Nations Sustainable Development Goals.

Discussion: Multidisciplinary action is required to update walking-related policy with embedded evaluation and governance mechanisms in all local walking systems. Furthermore, given sufficient collaboration across sectors, walking policy in Ireland has the potential to contribute to a wider breadth of national and global targets beyond the health, sport, tourism, and transport sectors.

KEYWORDS
walking, content analysis, physical activity policy, pragmatic, sustainable development goals

Introduction

The introduction of systems thinking in public health practice and research has provided stakeholders embedded within public health systems new perspectives on the interconnections between their own work, and the work of organisations from other sectors and disciplines in the system (1, 2). Many conceptual tools, such as applying a systems lens or "systems framing" have been adopted by researchers and practitioners to help stakeholders to develop a systems oriented view of the systems which they are embedded within (2, 3). Oftentimes, this involves asking stakeholders to "take a step back" and can offer stakeholders insight into the wider goals and systems that they influence/are influenced by. Physical activity (PA) policy researchers have begun to develop conceptual frameworks to assist with this notion of "zooming out" in order to understand the interconnections across policy sectors, disciplines and organisations involved in all stages of PA policy (4). At a global level, in 2015, the United Nations published the 2030 Agenda for Sustainable Development, which provides all member states of the United Nations a "shared blueprint for peace and prosperity for people and the planet" (5). At the core of the 2030 Agenda for Sustainable Development are 17 goals, termed the Sustainable Development Goals (SDGs). The SDGs require international, national, and local partnerships and policies to achieve high-level goals which aim to improve health, education, reduce inequalities, tackle climate change and end poverty across all United Nations member states (5).

The relationship between the SDGs and PA has garnered recent research attention. In a mixed methods paper, Salvo et al. (6) used agent-based modelling, a conceptual linkage exercise, and a scoping review of the literature to explore the synergy between at-scale PA promotion and the SDGs. Salvo and colleagues found at scale PA promotion may hold possible benefits for 15 SDGs (6). Moreover, Bauman (7) put forward an argument which outlines the potential for the sustainable development agenda to revitalise international PA promotion and research, by facilitating a broader, more systems-oriented view of the impacts of PA. Among many factors, the lack of upstream interventions, such as policies, promoting PA has led to stagnating physical inactivity levels globally and an evidence base congested with individual level, cross sectional studies (8, 9). The recent shift towards systems approaches to PA has begun to incorporate sectors beyond health, sport and transport in to conversations pertaining to PA (3, 10–12). However, ensuring PA policy and research decisions are transparent with global targets can supplement whole-of-systems approaches and can provide a new momentum to PA promotion (7).

Some organisations in the PA system have used the SDGs as a roadmap to determine the impact of their work and policies on the SDGs. For example, in a conceptual mapping exercise assessing the potential contribution of sports policies to the attainment of SDGs across countries in the Commonwealth, Sherry and colleagues (13) found direct links between some SDGs (SDG 3; SDG 4; SDG 10; and SDG 16) and actions within national sports policies across the Commonwealth. However, the findings also allowed Sherry and colleagues (13) to identify opportunities for sport policies to extend their scope and contribute to other SDG targets pertaining to much broader societal issues such as climate change (SDG 13). At a more granular level, Amosa and Lauff (14) determined the contribution of sport policies in Fiji and Samoa on the attainment of SDG goals through a similar conceptual mapping exercise. Amosa and Lauff found a list of context specific indicator datasets which can help monitor progress towards 132 of the 232 SDG indicators (14). Exercises such as those mentioned (6, 13, 14) can provide the opportunity to view the work of an organisation, or national level policies through an SDG lens. This, in turn, allows opportunities for data collection, intervention implementation, and policy development to be identified and informed. Although investment in promoting more walking and cycling has been suggested to be one of the "8 Investments that work for Physical Activity" (15), there is little known about how walking or cycling can specifically contribute to higher level goals.

Scotland's national walking promotion organisation, Paths for All, have made efforts to ensure alignment between the work conducted through the organisation at local and national level to global level objectives for PA outlined in the Global Action Plan for Physical Activity 2018–2030 (16, 17). In 2020, the Irish government have allocated €1 m per day to walking and cycling promotion and development (18), and there is an opportunity now to understand the potential contribution that increased walking levels may have on national and global targets. Get Ireland Walking, a national walking promotion organisation, was established in 2013 with the aim of intertwining the work of intersectoral and multidisciplinary organisations with a direct and indirect role in walking in Ireland at national level. The work of the organisation was guided by a national level action plan, the Get Ireland Walking Strategy and Action Plan 2017–2020 (GIW SAP) (19), following its publication in 2017. Gaining an understanding of how the work of Get Ireland Walking aligns with local level walking policies, national level targets, and the global agenda would benefit the next iteration of the GIW SAP. As of October 2022, Get Ireland Walking were undergoing the development stages of a new national walking strategy—succeeding the organisations' previous document—which will be published in 2023.

This aim of this paper is to provide a critical overview of walking policy at local and national level in Ireland across multiple domains using multiple methods with the intention of informing the next iteration of national walking policy in Ireland.

Methods and materials

This paper uses a mixed methods approach to analyse local and national level walking policies in Ireland across multiple domains. Firstly, a content analysis of local and national walking policies in Ireland was conducted. Secondly, conceptual linkage exercises were carried out to identify the potential contribution of walking, and the specific work of GIW, in attaining national and global level goals. The methods utilised for both objectives are described separately below.

Objective 1: conduct a content analysis of national and local level walking policies in Ireland

A content analysis of local and national level walking policies in Ireland was conducted using a multi-phased approach. As

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outlined in **Figure 1**, there were six phases involved in the content analysis of walking related policies in Ireland. The methods utilised in each phase is described below.

Phase 1: development of content analysis grid

To assess local and national level walking policy documents, a content analysis grid was developed and adapted from two existing PA policy audit/assessment tools. The two tools were: (1) The HARDWIRED criteria (20); and (2) the Comprehensive Analysis of Policy on Physical Activity (CAPPA) framework (21). The purpose of the development of a content analysis grid was to ensure a standardised process of assessing the quality of PA policies according to a set of indicators (22).

The CAPPA framework provides a conceptual framework within which to frame analyses of PA policy and was developed through an extensive review of literature, an open discussion between authors, a multiple phase Delphi process and a consultation process with PA policy stakeholders (21). The CAPPA framework allows researchers to situate and direct the scope of research studies relating to the assessment and auditing of PA policies across six categories: (1) Purpose of analysis; (2) Policy level; (3) Policy sector; (4) Type of policy; (5) Stage of policy cycle; and (6) Scope of the analysis. The "Scope of the Analysis" section outlines over twenty sample questions which users of the CAPPA framework can utilise to guide the analysis of PA policy across seven areas (Availability; Context; Processes; Actors; Political Will; Content; and Effects).

The HARDWIRED criteria are a set of characteristics of national PA-related policy which are deemed "absolutely essential" in order for PA policies to achieve successful outcomes at the population level (20). The methodology used by Bellew and colleagues (20) to develop the list of criteria comprised of a literature and policy review, audit of relevant websites, document searches and surveys of international stakeholders. The criteria are: (1) Highly consultative in development; (2) Active through multi-strategic, multi-level, partnerships; (3) Resourced adequately; (4) Developed in stand-alone and synergistic policy modes; (5) Widely communicated; (6) Independently evaluated; (7) Role-clarified and performance delineated; (8) Evidence-informed and Evidence-generating; and, (9) Defined national guidelines for health enhancing physical activity. Short statements are provided for each criterion, allowing users of the HARDWIRED criteria to rate PA policies of interest in accordance with the extent they meet the criteria.

To combine both tools, questions were formulated by the lead researcher (DP) which represented the short statements outlined within each of the HARDWIRED criteria and combined with the corresponding heading of the Scope of the Analysis section in the CAPPA framework (**Supplementary file S1**). Following this process, a combined list of questions ($n = 36$) across the seven headings in the scope of the analysis section of the CAPPA framework (21) was developed. Several questions deemed to be eliciting similar information were removed and a final composite content analysis tool containing twenty-three ($n = 23$) questions was used to assess local and national level walking policies in Ireland (**Supplementary file S1**). The approach taken to PA policy content analysis replicates the process used by Daugberg and colleagues (22), who used a content analysis grid across a range of indicators to analyse the contents of 27 national PA policies in the European region.

Phase 2: desktop search for presence of local walking polices

Formative research was conducted to provide the contextual backdrop to local and national walking policies in Ireland. Firstly, online searches of local authority websites and grey literature were conducted which aimed to investigate the presence of local level walking policies for all counties within the Republic of Ireland ($n = 26$). Local Authority, Local Sports Partnership, and other relevant websites were searched manually for policy documents relating to the promotion and development of walking. Formal written policies, as per the definition offered by Klepac-Pogrmilovic et al. (21), which focused specifically on the promotion and development of walking or included walking as part of an active travel or walking and cycling related strategy, were included for analysis. County Development Plans (CDP) and Local Sports Partnership Strategic Plans were not included for analysis as not all counties had published a CDP at the time of analysis and is beyond the scope of the current study.

Phase 3: local level verification phase

An employee of all Local Sports Partnerships ($n = 29$) was purposively recruited ($n = 18$, 69% response rate) for a short follow up phone call. The purpose of the phone calls was to clarify the findings of the desktop research (Phase 2). Contact details were obtained from the openly accessible Sport Ireland directory of Local Sports Partnership contact details on the Sport Ireland website. Findings relating to the presence of walking

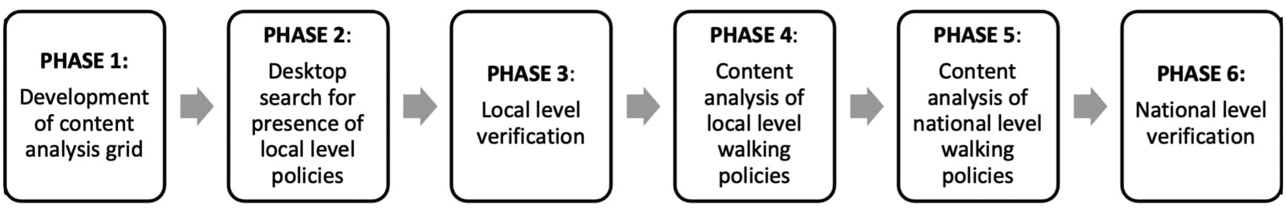

FIGURE 1
Workflow for local and national level walking policy analysis.

related policies in each county were separated into three categories: (a) No walking policy document; (b) Outdated walking policy; and (c) Walking policy present (2015-present). All policy documents retrieved from the online search which met the inclusion criteria and were in the implementation phase no earlier than 2015 were included for further analysis using the adapted content analysis grid developed in Phase 1. All policies found to meet these criteria but preceded 2015 were labelled as "outdated" and not included for further analysis. Policies older than 2015 were excluded due to changes in many contextual factors including COVID-19.

Phase 4: content analysis of local level walking policies

The content of each local level walking policy was investigated by the lead researcher (DP) through the application of the content analysis grid. The use of a content analysis grid allows researchers to identify differences among documents according to a list of criteria. The lead researcher (DP) screened each local level walking policy and provided statements for each of the criterion ($n = 23$) outlined within the content analysis grid. The accuracy of the statements provided for each policy were clarified by the authorship team (NM & BL).

Phase 5: content analysis of national level walking specific policies

Given the embedded role of the lead researcher (DP) within Get Ireland Walking and the academic and practical experience of the authorship team (BL & NM) in the areas of PA promotion and policy development in Ireland, there was a pre-existing knowledge base in relation to national level walking specific policies in Ireland. Get Ireland Walking's first strategic document, the GIW SAP (19), was published in 2017 and was the only national level walking specific policy document at the time of writing. The GIW SAP outlined 41 actions to be delivered across seven thematic areas by 30 multidisciplinary organisational partners.

Phase 6: national level verification

Following the process outlined in Phase 5, a senior member of the GIW staff provided additional details and substantiated the findings in an online meeting which was convened between the lead researcher (DP) and the programme manager of GIW. Specific clarification was sought on questions relating to context (Question 4), processes (Questions 6 and 7), actors (Questions 9 and 11), and political will (Question 12) (**Supplementary File S1**).

Objective 2: assess the contribution of (a) walking, and (b) Get Ireland Walking Strategy and Action Plan 2017–2020, to attaining national and global level targets

Conceptual linkage exercises were conducted to understand the contribution of walking, and the GIW SAP, to attaining Ireland's national targets and global level targets set by the United Nations. **Figure 2** outlines the workflow involved in the completion of all conceptual linkage exercises conducted as part of this study. The Government of Ireland published the National Development Plan 2021–2030 which outlines ten National Strategic Outcomes (NSOs) for the Irish government to achieve over a ten year period in relation to health, transport, education, and climate change (23). At the global level, the 2030 Agenda for Sustainable Development published by the United Nations outlines 17 goals, termed the Sustainable Development Goals (SDGs), which require international, national, and local partnerships to achieve high-level goals which aim to improve health, education, reduce inequalities, tackle climate change and end poverty across all United Nations member states (5).

Conceptual linkage exercises were conducted to assess how the GIW SAP may contribute to attaining national (NSOs) and global (SDGs) targets which were identified as relevant to walking. All the conceptual linkage exercises followed a similar process to that described by Salvo et al. (6), which relied on deductive logic and the expertise of researchers.

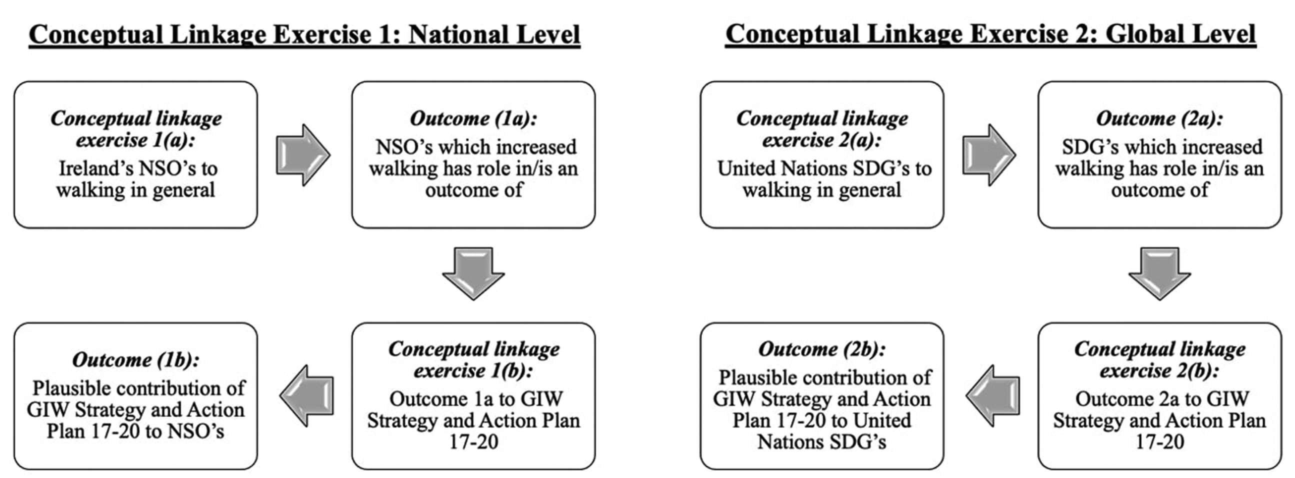

FIGURE 2
Conceptual linkage exercises workflow. (NSOs, National Strategic Outcomes; SDG's, Sustainable Development Goals).

Conceptual linkage exercises 1(a) and 2(a): the contribution of walking to national and global goals

Members of the authorship team (DP & NM) are involved in forthcoming work from inFocus Consulting and Sport Ireland which identified 11 SDGs and 47 SDG targets that were related to PA, physical education, and sport policy in Ireland. These findings were used as the basis of the current study. Therefore, at the global level, 47 SDG targets from 11 SDGs were screened and rated in accordance to their relevance to walking. At the national level, 89 targets from 10 NSOs were screened and rated in accordance to their relevance to walking. Walking, in this context, means "more people walking more often" and can hold a bidirectional relationship with SDG targets. For example, SDG Target 3.4 "By 2030, reduce by one third premature mortality from non-communicable diseases through prevention and treatment and promote mental health and well-being" can be partly achieved through increased levels of PA which can be partly obtained by increases in walking levels at the population level. In another example, the SDG Target 11.7 "By 2030, provide universal access to safe, inclusive and accessible, green and public spaces, in particular for women and children, older persons and persons with disabilities" can offer spaces and places for people to walk more often. The lead researcher (DP) conducted the initial screening and rated each SDG and NSO target in accordance to their relevance to walking (highly relevant; partially relevant; not relevant). This rating was subjective and relied on the knowledge of the researcher and their practical experience of being embedded in a national walking promotion organisation. The accuracy of the ratings assigned to all NSO and SDG targets by the lead researcher (DP) was confirmed by the authorship team (NM & BL) and disagreements were resolved through critical discussion.

Conceptual linkages exercise 1(b) and 2(b): the contribution of the Get Ireland Walking Strategy and Action Plan 2017–2020 to national and global level targets

A similar exercise was carried out to highlight the contribution of specific actions within the GIW SAP ($n = 41$) to global (SDG) and national (NSO) goals. Only SDG and NSO targets identified as highly relevant and partially relevant to walking in conceptual linkage exercises 1(a) and 2(a) were included for further analysis exercises 2(a) and 2(b), respectively. The United Nations SDG targets and the GIW SAP actions were linked if the successful implementation of the Get Ireland Walking action, at scale, was identified by the lead author (DP) and authorship team (NM & BL) to have the potential to contribute to attaining an SDG target. For example, SDG target 3.4 "By 2030, reduce by one third premature mortality from non-communicable diseases through prevention and treatment and promote mental health and well-being" can partly be achieved through increasing PA levels in those which are the most inactive. Get Ireland Walking implement community-based walking programmes nationally which target inactive population groups, and is an action outlined in the GIW SAP (Action 5.1) (19). The lead researcher (DP) in the current example, identified a plausible contribution of the successful implementation of Action 5.1 in the GIW SAP and the attainment of SDG target 3.4. This process was replicated for all SDG and NSO targets. The authorship team (NM & BL) confirmed the accuracy of the initial ratings of the lead researcher (DP) and disagreements were resolved through critical discussion.

Results

Objective 1: conduct a content analysis of national and local level walking strategies in Ireland

Local level walking policies in Ireland

Overall, the findings from this study suggest that half ($n = 13$) of counties in the Republic of Ireland do not currently, or have never had, a walking related local level policy document. **Figure 3** provides a map of the counties within the Republic of Ireland according to the presence of local level walking policies. For the counties that were found to have a local level walking policy in the implementation phase between 2015 and the time of writing ($n = 8$) (24–31), only one county (Cork) (24) was found to have a walking specific policy. The remaining policies contained walking related actions within a broader scope, including walking and cycling ($n = 1$) (29), tourism ($n = 2$) (28, 30), outdoor recreation ($n = 2$) (25, 31), urban design ($n = 1$) (27), and greenway development ($n = 1$) (26). Five counties were found to have outdated walking related policies. Of these, Waterford was the only county identified to have had a walking specific policy which, at the time of writing, was outdated by almost two decades (32). Below is a summary of results from the application of the content analysis grid to each walking related policy from 2015-present ($n = 8$). Full details of the content analysis can be found in **Supplementary file S2**.

Context

All local level walking related policies included in the content analysis ($n = 8$) were found to have outlined the broader policy context within which the policy sits. Furthermore, all policies outlined the relationship of the policy to other local and national policies from multiple sectors including health, planning, transport, and tourism. However, walking promotion and development was not the primary objective in all policies. One county (Wicklow) (31) specified the nature of funding sources supporting the implementation of the policy, whereas the funding sources supporting the implementation of policies in all other counties was unknown.

Processes

All policies included in the content analysis were consultative in development. The processes involved in policy development in all eight counties involved activities such as public meetings, interviews and online questionnaires. Less than half ($n = 3$) of local level policies included in the analysis conducted a context specific needs assessment to direct the actions within the policies

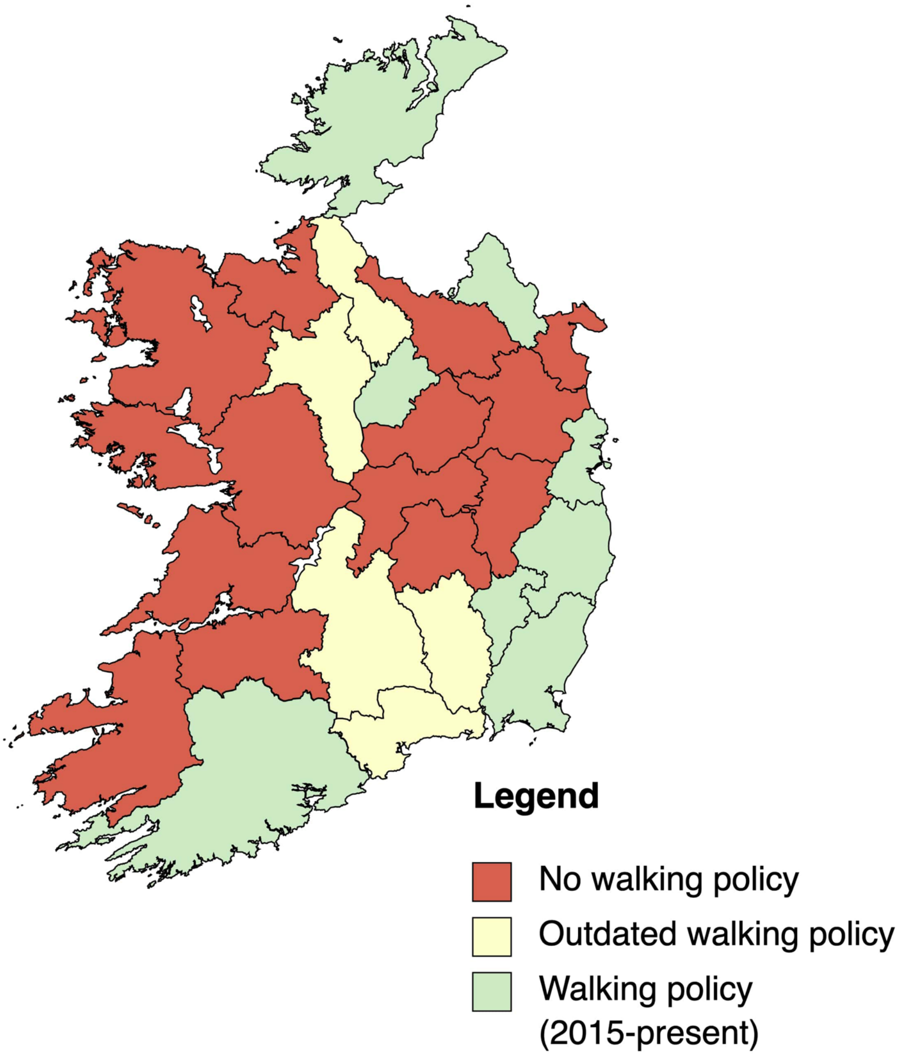

FIGURE 3
County by county breakdown of presence of walking policies. (Credit: mapchart.net).

(28–30). The majority ($n = 5$) (24, 25, 28–31) of policies included actions relating to the development of a communications strategy to support the implementation of the policy.

Actors

All ($n = 8$) policies were multidisciplinary in nature. Organisations from multiple sectors including health, outdoor recreation, sport, local government and tourism were engaged in the development processes of all policies included in the analysis.

Political will

There was no information relating to sustained political and stakeholder support on an ongoing basis or in the development process of any policy included in the analysis.

Content

Seven of the eight policies outlined the identified timelines for the implementation period of the policy (24, 25, 27–31). One policy (Donegal) (26) specified no timeframe for implementation. Half ($n = 4$) (25, 28, 30, 31) of the policies included a combination of upstream and downstream actions, one policy contained predominantly downstream actions (29), two (26, 27) contained predominantly upstream actions, and one was unclear (24).

Effect

The evaluation and monitoring mechanisms included in most policies was poor. Over half ($n = 5$) (21, 24, 26, 27, 30) of the policies did not specify any mechanisms to evaluate the implementation of the policy. For those that did ($n = 3$), two were found to include internal monitoring mechanisms, i.e., stakeholders self-report implementation progress (28, 29) and one highlighted a local university as a body that would assist with evaluation (25).

National level walking policies in Ireland

The following sections provides an overview of the application of the composite policy content analysis tool to the only walking-specific national level strategic document in Ireland, the GIW SAP (19) (see **Table 1**).

TABLE 1 Content analysis of the Get Ireland Walking Strategy and Action Plan 2017–2020.

Scope of policy analysis section	Composite policy audit checklist	Get Ireland Walking Strategy and Action Plan (2017–2020)
Availability	1. Is there a national walking strategy for Ireland?	Yes.
Context	2. What was the key stimulus for policy action?	The previous year (2016) saw the publication of Ireland's first National Physical Activity Plan, within which Get Ireland Walking were a key partner on delivering Action 43 aimed to increase the number of community walking programmes across the Local Sports Partnership network by 100 per annum.
	3. Were local level strategies developed according to the separation of powers doctrine?	No. However, there is work ongoing in Cork as part of a PhD project which will feed into the next iteration of the national strategy.
	4. What budget was allocated for the implementation of the policy?	No specific budget for the implementation of Strategy. In 2017, the initiative received €145k from Sport Ireland and Healthy Ireland. The Get Ireland Walking initiative was awarded an additional €100k through Dormant Accounts funding in 2018.
	5. Does the policy have a clear statement which is also embedded in other policy agendas?	The vision of Get Ireland Walking is to maximise the amount of people who walk regularly on the island of Ireland. Smarter Travel and the Design Manual for Urban Roads and Streets are both related policy documents yet outline a broader agenda.
Processes	6. What process did the strategy have to go through to be implemented?	Advisory group drafted initial draft of the Strategy. Individual interviews with stakeholders ($n = 30$) from government agencies, sporting bodies, charities, and not-for-profit were conducted to determine actions they could they lead on and could collaborate on. Stakeholder decided whether they could lead or collaborate on specific actions.
	7. Was a stakeholder analysis and needs assessment conducted to ensure widespread representation from interdisciplinary stakeholders at the early stages of strategy development?	Members of the advisory group ($n = 15$) (chaired by Sport Ireland) nominated relevant stakeholders to engage in the strategy development process. No reference to stakeholder analysis or needs assessment.
	8. What mechanisms are in place to support the dissemination of the strategy?	Action 1.1: Develop and implement a three-year Get Ireland Walking communications strategy. Get Ireland Walking communications strategy was published in 2019. No document outlining tailoring of Strategy content to needs of heterogenous stakeholders i.e., policymakers, researchers.
Actors	9. Does the strategy engage with grassroots practitioners, as well as policymakers, and define the organisational links between them?	30 partners organisations from multiple sectors mentioned as key partners and/or collaborators in the strategy. Organisations operate at levels ranging from policymakers to local level practitioners.
	10. What were the power relations between the actors involved in the development process?	Organisations involved at the consultation process, although have local level work programmes, all operate nationally. Organisations such as Department of Health, Health Service Executive and Sport Ireland are key policymaking organisations and provide core funding to other organisations on the list of partners and collaborators. For example, Local Sports Partnerships funded by Sport Ireland, Irish Heart Foundation part-funded through Health Service Executive.
	11. Were actions within the strategy progressed through intersectoral partnerships?	Yes, as most actions within the strategy were the responsibility of organisations from multiple sectors. However, no insight into the extent to which actions were implemented or evaluated. Progressed monitored only through self-report traffic light system (annually).
Political will	12. Did any political actor in power publicly express support to the development of the strategy?	An Taoiseach Leo Varadkar and Minister for Health Minister Simon Harris officially launched the Strategy in 2017.
	13. Is there a stable base of political and stakeholder support as well as sustained investment over the long term?	The Get Ireland Walking initiative is funded through dormant accounts funding, Healthy Ireland and Sport Ireland funding streams and is reviewed on an annual basis.
	14. Does the government hold regular discussions with the aim to support the implementation of the strategy?	No.
Content	15. Are the roles and responsibilities of organisations involved in strategy implementation well clarified and is there a common understanding of and agreement on how "successful implementation" is to be defined and measured?	Organisations have been assigned as either (a) lead partners of (b) collaborators on all actions within the Strategy. No consensus on successful implementation, evaluation, or dates for accountability purposes outlined. Progressed monitored only through self-report traffic light system (annually).
	16. Does the strategy have a clear statement on the timeframe for policy implementation?	Yes (2017–2020). Annual deadlines assigned to the implementation of specific actions. Get Ireland Walking implements an operational plan internally with the support and guidance of the National Governing Body, Mountaineering Ireland.
	17. Does the strategy reference specific target groups?	Yes. Actions within various themes focus on children and young people, mental health service users, and community-based walking programmes for inactive populations. Lead organisations are assigned to each action.
	18. Is the policy content predominantly "downstream" or "upstream"?	Combination of both. There are both examples of actions which pertain to the implementation of community-based programmes (downstream) and

(*continued*)

TABLE 1 Continued

Scope of policy analysis section	Composite policy audit checklist	Get Ireland Walking Strategy and Action Plan (2017–2020)
		facilitating policy alignment across sectors (upstream) mentioned within the strategy.
	19. Does the strategy outline a comprehensive approach using multiple strategies at multiple levels targeting multiple population groups?	Yes. The Strategy outlines actions which range from individual level interventions to higher level interventions.
Effects	20. Is the evaluation conducted by an independent body which is not connected to the government or "policy owners"?	The overall Get Ireland Walking initiative was evaluated by a consultancy company in 2022. The evaluation involved the co-development of key performance indicators and evaluated Get Ireland Walking on progress to those key performance indicators since 2013. Self-report traffic light system was in place throughout the implementation of the Strategy results are unknown.
	21. Is there systematic surveillance of population levels of walking?	Yes. The Irish Sports Monitor monitors trends in self-reported recreational and transport walking data biannually in Ireland. Transport related walking monitored in Census every five years.
	22. What kind of impact did the strategy have on walking levels?	Unknown/Not measured.
	23. Were there any unintended consequences of the implementation of the strategy?	Unknown/Not measured.

Context

Get Ireland Walking received funding from Sport Ireland and Healthy Ireland 2017. In 2018, annual funding for the initiative increased through the Dormant Account funds. The GIW SAP, at the time of publication, sat within the broader national PA policy context in Ireland. For example, Action 43 of the National Physical Activity Plan 2016–2020 (33) outlines Get Ireland Walking as a lead partner. Although Get Ireland Walking has both national and local remits, the GIW SAP was found to lack local level delivery mechanisms which feed into the implementation of the GIW SAP at national level. Given the lack of political leverage of Get Ireland Walking, there was little capacity to embed actions into interagency programmes of work to ensure accountability and transparency.

Processes

In order to progress the GIW SAP to the implementation phase, the Get Ireland Walking advisory group, consisting of 15 stakeholders from Sport Ireland, the Department of Health, Get Ireland Walking, the Health Service Executive, Ireland Active, the Irish Heart Foundation, and Mountaineering Ireland, developed the preliminary list of actions and nominated organisations to implement the actions as lead organisations or collaborators. Following this, a consultation process of 30 individual interviews with partner organisations were conducted in 2016 to determine the capacity for nominated organisations to act as lead partners or collaborators on assigned actions.

Actors

Actions within the GIW SAP were assigned to intersectoral organisations operating at multiple levels. For example, the GIW SAP engages with organisations operating at grass roots level (i.e., Local Sports Partnership network) and policymakers (i.e., Department of Health). Progress relating to the implementation of the actions within the GIW SAP were monitored through an annual self-report monitoring report completed by organisations. This was completed inconsistently over the implementation period of the GIW SAP.

Political will

Throughout the development process of the GIW SAP, no government official or political figure supported or engaged in the development process of the GIW SAP. However, the GIW SAP was officially launched by An Taoiseach (Prime Minister) Leo Varadkar and Minister for Health Simon Harris in 2017.

Content

The overall implementation period of the GIW SAP is clearly defined (2017–2020) and annual timelines are assigned to each action (i.e., completed by end of 2019). The content of the actions and thematic areas outlined within the GIW SAP varies and outlines actions and sections which focus on specific target groups (i.e., children and young people). Although lead partners and collaborators are assigned to each action, the exact roles of each organisation and what represents successful implementation is not stated.

Effects

The GIW SAP was not evaluated independently. However Get Ireland Walking (as an initiative of Sport Ireland) was independently evaluated in 2022. Progress on the implementation of the GIW SAP was monitored annually through stakeholders self-reporting their progress on actions according to a traffic light system. Although the Irish Sports Monitor is an established national level survey measuring self-reported recreation and transport walking, the impact of the SAP on population levels of walking in Ireland is unknown.

Objective 2: assess the contribution of (a) walking, and (b) Get Ireland Walking Strategy and Action Plan 2017–2020, to attaining national and global level targets

The results for Objective 2 are presented in four sections. Each section relates to the outcomes of the four conceptual linkage exercises outlined in **Figure 2** to assess the contribution of walking to attaining global and national level targets (1a and 2a),

TABLE 2 National strategic outcomes (NSO) and associated NSO targets identified as relevant to walking.

National Strategic Outcome	National Strategic Outcome Target Statement	NSO target relevance to walking
NSO 1: Compact Growth	1.1 - Enable urban infill development that would not otherwise occur	Partially relevant
	1.2 - Improve “liveability” and quality of life, enabling greater densities of development to be achieved	Highly relevant
	1.3 - Encourage economic development and job creation, by creating conditions to attract internationally mobile investment and opportunities for indigenous enterprise growth	Partially relevant
	1.4 - Building on existing assets and capacity to create critical mass and scale for regional growth	Partially relevant
	1.5 - Improve accessibility to and between centres of mass and scale and better integration with their surrounding areas	Highly relevant
	1.6 - Ensure transition to more sustainable modes of travel (walking, cycling, public transport) and energy consumption (efficiency, renewables) within an urban context	Highly relevant
	1.7 - Encourage labour mobility to support employment-led growth, including affordable housing, education/skills development and improved community and family services including childcare	Partially relevant
	1.8 -Enhance the attractiveness, viability and vibrancy of smaller towns and villages and rural areas as a means of achieving more sustainable patterns and forms of development	Highly relevant
	1.9 - Ensure transition to more sustainable modes of travel (walking, cycling, public transport) and energy consumption (efficiency, renewables) within smaller towns and villages and rural areas	Highly relevant
	1.12 - Cross-boundary collaboration at county and regional level to achieve more sustainable outcomes for rural communities, e.g. applicable to shared settlements, landscapes and amenities as well as lands in state ownership	Partially relevant
NSO 2: Enhanced Regional Accessibility	2.3- Enabling more effective traffic management within and around cities and re-allocation of inner city road-space in favour of bus-based public transport services and walking/cycling facilities	Highly relevant
	2.8 - To strengthen public transport connectivity between cities and large growth towns in Ireland and Northern Ireland with improved services and reliable journey times	Partially relevant
NSO 3: Strengthened Rural Economies and Communities	3.1 - Implementation of the actions outlined in the Action Plan for Rural Development	Partially relevant
	3.3 - Implementation of a targeted Rural Regeneration and Development Fund to enable opportunities to secure the rejuvenation and re-purposing of rural towns and villages weakened by the structural changes in rural economies and settlement patterns	Partially relevant
	3.4 - Provide a quality nationwide community based public transport system in rural Ireland which responds to local needs under the Rural Transport Network and similar initiatives	Partially relevant
	3.5 – Invest in maintaining regional and local roads and strategic road improvement projects in rural areas to ensure access to critical services such as education, healthcare and employment	Partially relevant
	3.6 - Invest in greenways, blueways and peatways as part of a nationally coordinated strategy	Highly relevant
NSO 4: Sustainable mobility	4.1 - Expand attractive public transport alternatives to car transport to reduce congestion and emissions and enable the transport sector to cater for the demands associated with longer-term population and employment growth in a sustainable manner through the following measures	Highly relevant
	4.2 - Deliver the key public transport objectives of the Transport Strategy for the Greater Dublin Area 2016–2035 by investing in projects such as New Metro Link, DART Expansion Programme, BusConnects in Dublin and key bus-based projects in the other cities and towns	Partially relevant
	4.3 - Provide public transport infrastructure and services to meet the needs of smaller towns, villages and rural areas	Partially relevant
	4.4 - Develop a comprehensive network of safe cycling routes in metropolitan areas to address travel needs and to provide similar facilities in towns and villages where appropriate	Partially relevant
NSO 7: Enhanced Amenities and Heritage	7.1 - Implementation of planning and transport strategies for the five cities and other urban areas will be progressed with a major focus on improving walking and cycling routes, including continuous greenway networks and targeted measures to enhance permeability and connectivity	Highly relevant
	7.2 - The Rural and Urban Regeneration and Development Funds will support transformational public realm initiatives to give city and town centre areas back to citizens, encouraging greater city and town centre living, enhanced recreational spaces and attractiveness from a cultural, tourism and promotional perspective	Highly relevant
	7.3 - We will conserve, manage and present our heritage for its intrinsic value and as a support to economic renewal and sustainable employment	Partially relevant
	7.4 - Open up our heritage estates to public access, where possible	Highly relevant
	7.5 - Invest in and enable access to recreational facilities, including trails networks, designed and delivered with a strong emphasis on conservation, allowing the protection and preservation of our most fragile environments and providing a wellbeing benefit for all	Highly relevant
NSO 10: Access to Quality Childcare, Education and Health Services	10.1 - Provide additional investment in the schools sector to keep pace with demographic demand and to manage increasing building and site costs so that new and refurbished schools on well-located sites within or close to existing built-up areas, can meet demographic growth and the diverse needs of local population	Highly relevant
	10.2 - Expand and consolidate third-level facilities at locations where this will further strengthen the capacity of those institutions to deliver the talent necessary to drive economic and social development in the regions. The consolidation of the DIT campus at Grange Gorman is a critical flagship infrastructural project for the higher education sector	Partially relevant

TABLE 3 Sustainable development goals and associated SDG targets identified as relevant to walking.

SDG	SDG target	SDG target relevance to walking
SDG 3: Good health and well-being	3.4: By 2030, reduce by one third premature mortality from non-communicable diseases through prevention and treatment and promote mental health and well-being	Highly relevant
	3.5: Strengthen the prevention and treatment of substance abuse, including narcotic drug abuse and harmful use of alcohol	Partially relevant
	3.6: By 2020, halve the number of global deaths and injuries from road traffic accidents	Highly relevant
	3.9: By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination	Partially relevant
SDG 11: Sustainable cities and communities	11.2: By 2030, provide access to safe, affordable, accessible and sustainable transport systems for all, improving road safety, notably by expanding public transport, with special attention to the needs of those in vulnerable situations, women, children, persons with disabilities and older persons	Highly relevant
	11.3: By 2030, enhance inclusive and sustainable urbanisation and capacity for participatory, integrated and sustainable human settlement planning and management in all countries	Highly relevant
	11.6: By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management	Highly relevant
	11.7: By 2030, provide universal access to safe, inclusive and accessible, green and public spaces, in particular for women and children, older persons and persons with disabilities.	Highly relevant
	11.a: Support positive economic, social and environmental links between urban, peri-urban and rural areas by strengthening national and regional development planning.	Highly relevant
SDG 4: Quality Education	4.7: By 2030, ensure that all learners acquire the knowledge and skills needed to promote sustainable development, including, among others, through education for sustainable development and sustainable lifestyles, human rights, gender equality, promotion of a culture of peace and non- violence, global citizenship and appreciation of cultural diversity and of culture's contribution to sustainable development	Partially relevant
SDG 8: Decent work and economic growth	8.1: Sustain per capita economic growth in accordance with national circumstances and, in particular, at least 7 per cent gross domestic product growth per annum in the least developed countries	Partially relevant
	8.9: By 2030, devise and implement policies to promote sustainable tourism that creates jobs and promotes local culture and products	Highly relevant
SDG 12: Responsible consumption and production	12.8: By 2030, ensure that people everywhere have the relevant information and awareness for sustainable development and lifestyles in harmony with nature	Partially relevant
	12.2: By 2030, achieve the sustainable management and efficient use of natural resources	Partially relevant
SDG 13: Climate action	13.2: Integrate climate change measures into national policies, strategies and planning	Partially relevant
SDG 16: Peace, justice and strong institutions	16.6: Develop effective, accountable and transparent institutions at all levels	Partially relevant
	16.7: Ensure responsive, inclusive, participatory and representative decision- making at all levels	Partially relevant
SDG 17: Partnerships for the goals	17.16: Enhance the Global Partnership for Sustainable Development, complemented by multi-stakeholder partnerships that mobilise and share knowledge, expertise, technology and financial resources, to support the achievement of the SDGs in all countries, in particular developing countries	Partially relevant
	17.17: Encourage and promote effective public, public– private and civil society partnerships, building on the experience and resourcing strategies of partnerships	Partially relevant

and the contribution of the GIW SAP to attaining global and national level targets (1b and 2b).

Conceptual linkage exercise 1(a): the contribution of walking in attaining national level targets in Ireland

Overall, there were 88 NSO targets across 10 NSOs which were screened by the authorship team. Following the conceptual linkage exercise, 28 NSO targets within six NSOs were identified to hold bi-directional relationships to walking. Specific target statements were identified within NSOs which were related to sustainable mobility (NSO 4), strengthening local economy (NSO 3), improving access to amenities (NSO 7), quality education and healthcare (NSO 10), intercity accessibility (NSO 2) and sustainable growth of towns and cities (NSO 1). **Table 2** highlights the full list of NSO targets which were identified as partially or highly relevant to walking. Of the 28 NSO target statements identified as relevant to walking, over half ($n = 15$) of the targets were identified as highly relevant to walking.

Conceptual linkage exercise 2(a): the contribution of walking in attaining global level targets

Forty-seven ($n = 47$) SDG targets from 11 SDGs were screened in accordance to their relevance to walking by the authorship team. Overall, there were 8 SDGs (SDG 3; SDG 4; SDG 8; SDG 11; SDG 12; SDG 13; SDG 16; and SDG 17) which were identified as relevant to walking. More specifically, 19 SDG targets across the 8 SDG's were found to be highly relevant ($n = 8$, 42%) or partially relevant ($n = 11$, 58%) to walking. The full list of SDG targets and their relevance to walking can be found in **Table 3**.

Conceptual linkages exercise 1(b): the contribution of the Get Ireland Walking Strategy and Action Plan 2017–2020 to Ireland's national strategic outcomes

The findings of the conceptual linkage exercise investigating the contribution of the GIW SAP to Ireland's national level governmental targets (NSOs), suggest that actions in six out

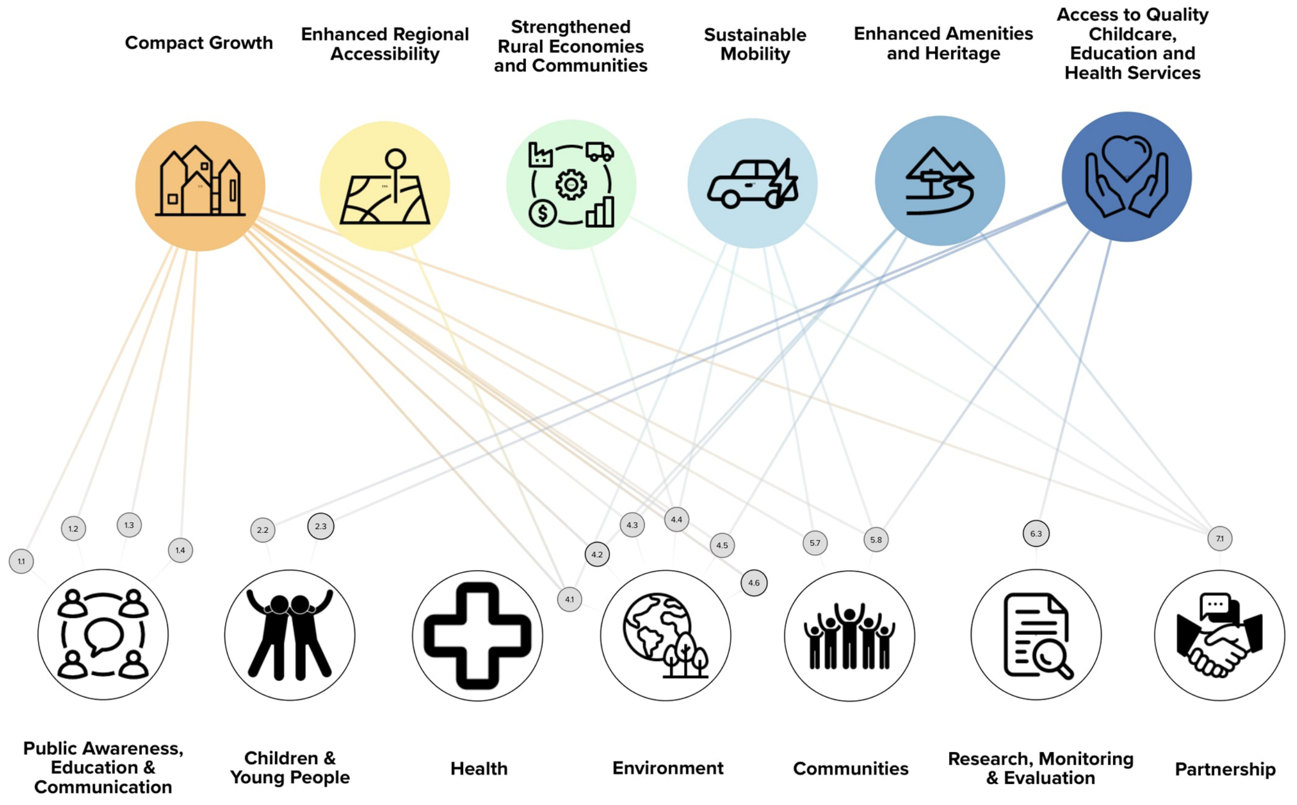

FIGURE 4
Walking related NSO's and NSO targets (Top row) and their links to actions within the themes of the Get Ireland Walking Strategy and Action Plan 2017–2020 (bottom row) (solid line = NSO target identified as highly relevant to walking; dashed line = NSO target identified as partially relevant to walking.

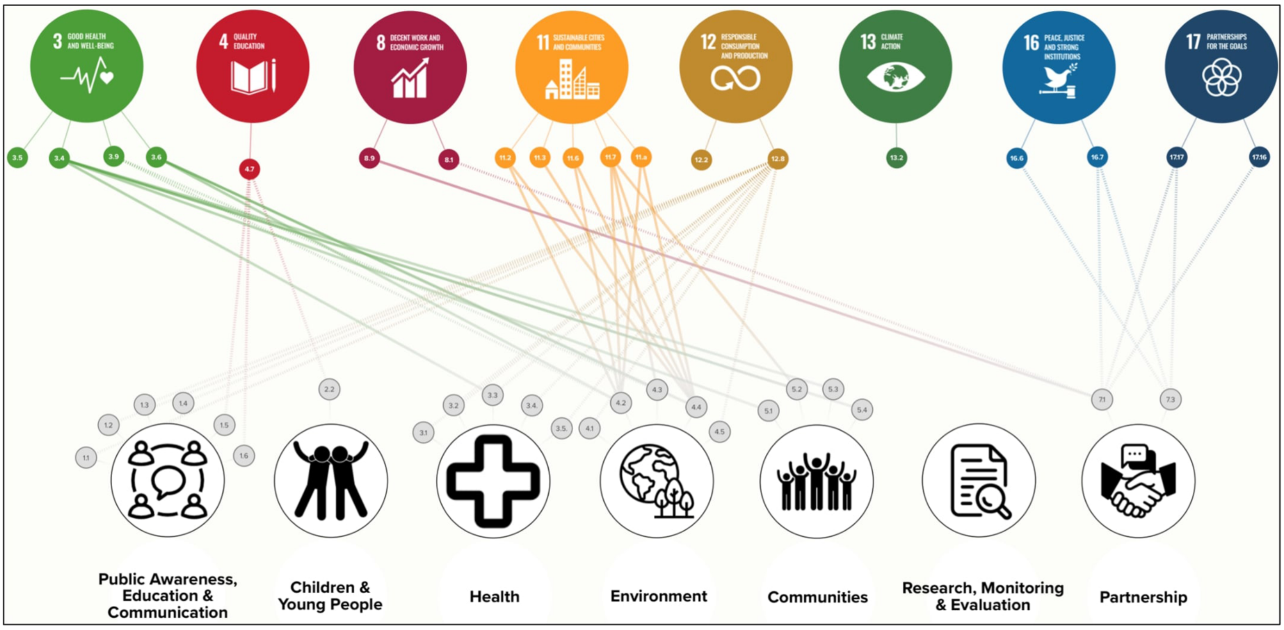

FIGURE 5
Walking related SDG's and SDG targets (Top row) and their links to actions within the Get Ireland Walking Strategy and Action Plan 2017–2020 (bottom row) (solid line = SDG target identified as highly relevant to walking; dashed line = SDG target identified as partially relevant to walking).

seven of the thematic areas listed in the GIW SAP may contribute to six out of ten NSOs. Figure 4 provides an overview of the potential contribution of actions within the GIW SAP to NSO targets. There were a total of 17 GIW SAP actions which were identified to plausibly contribute to attaining 27 NSO targets. The most explicit contributions of actions within the GIW SAP to NSOs were between the Environment theme in the GIW SAP and NSO 1 (Compact Growth) and NSO 7 (Enhanced Amenities and Heritage). Actions within the Environment theme of the GIW SAP were found to hold the potential to contribute to five out of six of the walking related NSOs. There were no actions within the Health theme of the GIW SAP that were identified as contributing to the attainment of any NSO targets. A full list of the GIW SAP actions and their conceptual linkages with NSO targets can be found in **Supplementary file S3**.

Conceptual linkages exercise 2(b): the contribution of the Get Ireland Walking Strategy and Action Plan 2017–2020 to the united nations sustainable development goals

The findings of the conceptual linkage exercise exploring the connection between the GIW SAP and SDG targets suggest that there are ample opportunities to increase the scope of SDG-relevant actions within future iterations of the GIW SAP. For example, the most explicit links between GIW SAP actions and SDG targets were identified between actions in the Environment and Communities themes with SDG 11 (Sustainable Cities and Communities) and SDG 3 (Good Health and Wellbeing), respectively. However, actions across six themes in the GIW SAP were identified as potential contributors to SDG targets across six SDG's. Figure 5 provides a visualisation of the actions within the GIW SAP which could plausibly contribute to the attainment of SDG targets. There was a total of twenty-three ($n = 23$) actions within the SAP which held partial and highly relevant links to sixteen SDG targets. There were three SDG targets (3.5; 12.2; 13.2) which were found to be partially relevant to walking, but not to actions within the GIW SAP. There were no actions within the Research, Monitoring and Evaluation theme of the GIW SAP which were relevant to any walking-related SDG targets. Similarly, there were no GIW SAP actions which held plausible links to the SDG 13 (Climate Action). Sustainable Development Goal 3 (Good health and wellbeing) and SDG 11 (Sustainable Cities and Communities) were found to have the highest number of SDG targets which were identified as highly relevant to actions within the SAP. All walking-related SDG targets in SDG 11 (Sustainable Cities and Communities) were found to hold highly relevant links to three actions in the Environment theme of the SAP, and one action in the Communities theme of the GIW SAP. A full list of the GIW SAP actions and their conceptual linkages with SDG targets can be found in **Supplementary file S4**.

Discussion

The aim of this study was to provide a critical overview of walking policy at local and national level in Ireland across multiple domains. The findings from this study are threefold. Firstly, the presence of walking specific local level policies is low. Furthermore, local level walking specific policies in Ireland were found to be vague in nature, lacking clarity on the roles and responsibilities of organisations and information relating to evaluation. Secondly, findings from the content analysis of national level walking policies found that the GIW SAP was, at its core, interdisciplinary in nature yet lacked clarity on the specific roles and responsibilities of organisations involved in the implementation and evaluation of the strategy. Moreover, the GIW SAP holds a national level scope, yet lacks local level delivery mechanisms to assist with the implementation. Thirdly, findings from the conceptual linkage exercises suggest that walking can contribute to many national and global targets, yet there are opportunities to increase the breadth of targets which walking, and the work of Get Ireland Walking, can have through whole-of-systems approaches.

Irish walking policy—synergies and specificities

Our results suggest that half of the counties in the Republic of Ireland have never had a local level policy with a specific walking focus. For the counties that have, five were dated before 2015, suggesting the need for renewal of some policies. The policies which underwent content analysis as part of the current study were found to be multidisciplinary in nature and were consultative in development. Bellew and colleagues (20) identify multidisciplinary action and consultation as necessities in successful PA related policy. However, ensuring strong monitoring mechanisms are embedded in PA policy is of utmost importance to the overall effectiveness of a policy (34, 35). There were very few examples of effective evaluation and monitoring mechanisms in local and national walking policies identified in the current content analysis. The lack of governance and accountability mechanisms embedded within local walking policies in Ireland found in the current study may be explained by local level walking system actors engaging in symbolic politics, where the development and publication of public policy provides an emblematic gesture to the public, with no real intention of implementation (36–38). However, the transdisciplinary nature of walking may also help explain the lack of governance and monitoring mechanisms in local walking policies in Ireland. Walking promotion and development is not the sole responsibility of one sector, organisation, or discipline. Previous work by our research group (11) has demonstrated the potential for systems science methods, specifically systems mapping, to assist with engaging multidisciplinary stakeholders at local level in Ireland. Although Power and colleagues used systems mapping as a catalyst to engage stakeholders, systems mapping can also help identify data sources and monitoring mechanisms during the stages of developing local walking policies (39).

The results of the content analysis suggest that local level policies included walking as part of broader agendas such as walking and cycling, tourism, and outdoor recreation. Cork and Waterford were found to be the only two counties in the Republic of Ireland which had published walking specific local level policies. Interestingly, both differ in their overall focus. The Cork City Walking Strategy 2013–2018 (24) focuses on the promotion of walking for transport, whereas Step by Step: Walking Strategy for Waterford (32) focuses predominantly on recreational walking. While there are examples of transport specific walking policies in Norway (40), and acknowledging walking as its own transport mode when collecting data and devising policies is recommended (41), it must be noted that this approach to local level walking policies may exacerbate disciplinary siloes. A more systems-oriented approach to walking policy has been adopted by Paths for All, a national walking promotion charity in Scotland (17). Adopting a similar approach to walking promotion in Ireland by embedding national level policy in the global agenda with local level implementation supports may be a positive step for walking promotion in Ireland. An organisation such as Get Ireland Walking has the potential to mobilise recent increases in funding allocated to walking in Ireland (18) and to act as a national level facilitator in cultivating a systems approach to walking through engaging organisations from across sectors and disciplines.

Similar to the majority of local level walking policies, the national level GIW SAP is multidisciplinary in nature and consultative in development. Ireland's only national walking specific policy document was developed after a period of consultation with stakeholders from sport, health, education, transport, and academia. Engaging with multiple sectors has been noted as best practice in the PA policy development literature (20, 21, 42). However, a study conducted by Power et al. (11) which used social network analysis methods to evaluate the communication network between the multidisciplinary actors involved in the implementation of the GIW SAP, found that there was a mismatch between how actors were required to communicate (based on collaborative actions in the GIW SAP) compared with how actors communicated in practice. The lack of clarity in relation to the roles and responsibilities of the stakeholders involved in the implementation of the GIW SAP may be explained by the lack of political leverage held by GIW. For example, GIW does not operate at a governmental level and has limited resources and thus does not hold the capacity to embed the GIW SAP actions within the work of collaborating organisations. For future iterations of national walking policy in Ireland, care should be taken to develop a common vision to ensure effective coordination for policy implementation (43, 44). More research is needed to understand potential for systems-oriented methods such as systems mapping and social network analysis to be embedded within PA policy evaluation plans in conjunction with more traditional methods. Doing so may help stakeholders to develop a common understanding of the policy system and to gain real time insights into the collaboration networks involved in policy implementation.

How can walking contribute to the attainment of national and global level goals?

Conceptual linkage exercises to explore the contribution of PA and sport to the United Nations SDGs have been conducted elsewhere (6, 13, 14) and the potential benefit to aligning the PA field to the SDGs has been outlined (7). The findings presented in this study build on the approaches used by Salvo et al. (6) and are applied specifically to walking. Using global and national goals as conceptual frameworks within which to view national walking policy in Ireland facilitated the identification of opportunities for deepening the potential contribution that walking can have attaining higher-level targets. However, the contribution of the GIW SAP to national level targets in Ireland is limited. For example, the most explicit contributions of the GIW SAP to the NSOs identified were from actions within the Environments and Communities themes. It has been suggested that PA is perceived to be the sole responsibility of organisations within the health, transport, and sport sectors, when in reality, there are a plethora of sectors who have a role to play (45, 46). The policy actions included in the Environments and Communities themes in the GIW SAP can be interpreted as playing a direct and explicit role in the promotion and development of walking, for example through the implementation of community-based walking programmes (19). However, there is potential to include a wider breadth of future GIW SAP actions that play an indirect role in attaining national level targets in Ireland with sufficient collaboration, coordination and alignment between stakeholders in the walking system.

The findings of the current study indicate that walking can possibly contribute to over half of Ireland's NSO's with ties to many sectors including urban design, planning, local government and transport. However, the contribution of GIW SAP actions were more explicitly relevant to the tourism, health, sport, research, and outdoor recreation sectors. Yet interestingly, many of the targets outlined within each of the NSOs do not explicitly mention walking, pedestrians, or PA—yet were still identified as partially or highly relevant to walking. The lack of breadth in terms of to the actions within the GIW SAP which were identified to potentially contribute to national targets may be partly explained by the context within which GIW is situated. The organisation is not an independent body and operates within Mountaineering Ireland, the national governing body for Mountaineering in Ireland, whose agenda predominantly focuses on the use of mountains and trails for recreational walking. The conceptual work of Piggin is mirrored in practice here within the Irish walking system. Piggin (47) advocates for a more holistic definition of PA which could help incorporate a wider breadth of sectors in policy decisions relating to PA. The use of NSOs and SDGs to facilitate a viewpoint of walking through a broader systems-oriented lens may allow for opportunities to identify organisations and decision makers outside of those who are already engaged in walking policy in Ireland to become evident. Doing so may lead to improved future iterations of Irish walking policy which are transparent with national and global targets.

Strengths and limitations

There are some limitations in this study. Firstly, although the approach taken to the conceptual linkage exercises mirrored the methods of Salvo et al. (6), there were fewer members of the research team for this study. This may have increased the risk of omitting linkages. However, the research team included a researcher embedded in Ireland's national walking promotion organisation (DP) and experienced researchers in PA policy in Ireland (BL & NM). This research provides a platform upon which to build on and confirm or refute the findings of the conceptual linkage exercise, as the identification of indicator datasets to clarify the existence of an empirical link between national walking policy and national and global goals was beyond the scope of this study. The exclusion of Local Sports Partnership strategic plans and County Development Plans from the analysis may have resulted in the omission of some local level walking related policy actions. The local level verification phase of the content analysis (Phase 3), only involved members of the Local Sports Partnerships network. It is plausible that individuals from other sectors may have provided different responses. However, the Local Sports Partnerships network represent a network of stakeholders embedded in local walking systems which provide the largest geographical spread, and thus were identified as the most appropriate contacts for the current study. This study is an example of how PA policy analysis tools can be used to inform the development of more effective walking strategies and policies that are aligned to national and international targets.

Conclusion

There is a need to update local and national walking policies in Ireland according to best practice criteria from international PA policy to ensure transparency and alignment across policy levels. This paper provides guidance to local and national walking systems in Ireland on (re)writing walking policies which are transparent with national and global agendas. With multidisciplinary action across walking systems, walking can help contribute to many national and global targets. Developing future policies which strengthen existing connections to national and global targets should be prioritised by local and national walking systems in Ireland.

Data availability statement

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

Ethics statement

This work is part of a PhD project which was granted ethical approval from the Ethics Committee at the School of Health Sciences, South East Technological University, Waterford.

Author contributions

DP, BL, and NM were involved in the conception and the study. DP organised the database and conducted initial phases of data analysis. BL and NM provided critical feedback on the interpretation of data. DP wrote the first draft of the manuscript. All authors contributed to the article and approved the submitted version.

Funding

This work was funded as part of a co-funded PhD scholarship (agency code: WIT_PhDCoFund_2019_23) between South East Technological University and Get Ireland Walking.

Acknowledgments

We would like to thank Nicola Briggs for her assistance with the desktop research and Jason King for providing feedback on the initial iterations of the content analysis of the Get Ireland Walking Strategy and Action Plan 17–20.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fspor.2023.1125636/full#supplementary-material.

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PUBLISHED 04 April 2023
DOI 10.3389/fpubh.2023.1049254

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SPECIALTY SECTION
This article was submitted to Children and Health, a section of the journal Frontiers in Public Health

RECEIVED 20 September 2022
ACCEPTED 14 March 2023
PUBLISHED 04 April 2023

CITATION
Ding P, Ding C and Feng S (2023) The health benefits of bicycling to school among adolescents in China: A propensity score matching study.
Front. Public Health 11:1049254.
doi: 10.3389/fpubh.2023.1049254

The health benefits of bicycling to school among adolescents in China: A propensity score matching study

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Background: A large number of high-income countries are now promoting active commuting to school as an opportunity for adolescents to increase physical activity (PA) and improve their health. Few studies have examined the multiple benefits of active travel to school among adolescents in developing countries, especially in China. Hence, this study aims to estimate the effects of bicycling to school on adolescents' subjective health, physical health, and sickness absence.

Methods: Self-reported and cross-sectional data from 6,353 school-aged children (12–19years old) in the 2014–2015 China Education Panel Survey (CEPS2014-2015) were used. The independent variable was a binary, self-reported indicator of whether children bicycled to school. The dependent variables included subjective health (self-reported health, mental stress), physical health (BMI, kidney disease, lung disease, heart disease, brain disease, upper limb fracture, lower limb fracture, and sickness frequency), and sickness absence. Propensity score matching (PSM) was used to estimate the causal effects of bicycling to school on adolescents' health.

Results: Bicycling to school positively affects both subjective and physical health. Those students who biked to school were associated with a higher self-rated health status, a healthier weight, a lower level of mental stress, and a lower risk of developing brain diseases. No significant relation is found between bicycling and sickness frequency, and sickness absence. Moreover, we separately compared the bicycling group with the walking group and the non-active travel group. There is still evidence that cycling is beneficial for students. Compared with walking to school, cycling to school resulted in a higher self-rated health score and a lower mental stress score. Physically, students who bicycled to school were less likely to be absent from school and suffer from kidney and brain diseases than students who walked to school. However, we do not find a significant difference in health outcomes from cycling compared to non-active modes of transportation. Further, differentiation of the health effects of bicycling across living areas shows that health effects are more pronounced for those living in edge and rural areas.

Conclusion: These findings provide evidence of the value of promoting bicycling to school in improving various adolescents' health outcomes in transitional China.

KEYWORDS
bicycling to school, adolescents, subjective health, objective health, sickness absence

1. Introduction

Insufficient physical activity among school-age adolescents is one of the most common problems worldwide. In China, 84.3% of adolescents were insufficiently physically active (1). Physical inactivity is linked to many chronic diseases, such as heart disease (2), kidney disease (3), and colon cancer (4). Moreover, according to the latest statistics released by the National Health Commission (2018), about 30 million Chinese children under 17 also suffer from various mood disorders and problems requiring comprehensive interventions (5). The prevalence highlighted the need for increased physical activity opportunities in adolescents to improve their physical and mental health.

Active commuting, defined as walking or bicycling to school, can easily incorporate PA into school-age children's daily life. Many researchers have examined a broad range of health benefits associated with active travel (often combining walking and bicycling). Studies have shown that active commuting is associated with better perceived physical health (6–9), increased levels of physical activity (10), as well as lower body mass indexes (11). Some studies further examined the role of active travel on mental health. Active commuting is associated with more positive emotions (12–14) and lower stress (15–18) than commuting by passive modes. Furthermore, active commuting has been found to reduce sickness absence (19, 20).

Some studies, however, have highlighted the different contributions of bicycling and walking to the health benefits (21), and a crude grouping could conceal some health benefits behind the choice of travel mode. Walking is the physical activity that is more prevalent among the population than bicycling and sufficient evidence for promoting walking to/from school (22). However, taken as a whole, there was less evidence supporting the health benefit of bicycling compared to walking. Further, cycling is more energy-intensive than walking (8). It was reported that vigorous activity has a greater health impact than moderate physical activity (23). Therefore, cycling to school may have a greater potential for increasing various health indicators than walking (24, 25). More research is needed to understand the relationship between biking to school and adolescents' health.

A large number of high-income countries are now promoting active commuting to school as an opportunity to increase adolescents' PA and improve their health (26–29). However, such efforts remain unclear in developing countries like China. To the authors' knowledge, although China has the world's largest school system, only one empirical study on active commuting to school among national representative adolescents has been conducted (11, 12, 30), and empirical evidence in previous literature in the western context may not apply directly to China's unique situation. First, with economic growth and greater use of automobile transportation in China, active commuting to school among young people has decreased from 84% in 1997 to 55.8% in 2010 (11, 12, 30). Second, the policy of school merging was implemented in rural areas from 2000 to 2010. After the adjustment to the school layout, the commuting distance for rural students was extended from 1.6 to 4.0 km (31), and long commuting time could have opposing effects on health (32, 33), the impact of bicycle to school on adolescents' health may be canceled out. Third, compared to developed countries, China's rapid urbanization has led to severe environmental problems (34), which may reduce the positive effects of bike commuting. Given these unique contexts, it is urgent to examine the effects of bicycling on Chinese adolescents' health so that effective policy can be developed.

We identify four gaps in the literature that motivate this research. First, previous studies show that a significant correlation exists between active travel to school and health, mostly based on surveys of a single health indicator; few papers comprehensively included various health outcomes in one analysis. Second, the conclusion reached by previous studies that a significant correlation exists between active commuting and health has been mostly combined with bicycling and walking together. There was less evidence, especially on the health benefit of bicycling. Third, previous research on child commute well-being has been dominated by studies from the U.S., Canada, and Europe, while few studies have paid specific attention to the development contexts of adolescents. Fourth, the association between commutes and health is complex and difficult to confirm. Most previous studies have examined the association through regression analysis, while few have explored the causal association using econometric techniques.

To fill these knowledge gaps, this study takes a more comprehensive approach to explore the effect of bicycling on adolescents' health: (a) We investigate whether bicycling to school improves children's health across several domains (subjective health, physical health, and sickness absence) rather than just one domain such as mental status or physical activity. (b) Using data from a nationally representative survey called the China Education Panel Survey; this paper examines the relationship between adolescent bicycle commuting and their health in China, the world's largest developing country. (c) Unlike previous studies that combined bicycle and walking trips as active commuting studies, specifically, this study compares the health benefits of bicycling with those of non-bicycling, walking, and other modes of passive commuting. (d) We use an econometric technique known as propensity score matching (PSM) to investigate causal effects rather than correlations. The methodology is described in the following section.

2. Method

2.1. Data

The data for this paper is drawn from the China Education Panel Survey (CEPS), the first nationally representative longitudinal survey of junior-high students conducted by the National Survey Research Center at the Renmin University of China. The data have been used in numerous studies, confirming their validity (35–40). The survey includes extensive information on students' socio-demographics, school travel modes, health, school management, and teacher qualities. The baseline survey is a random sample (applied a multistage sampling method with probabilities proportional to size) of approximately 20,000 students in 438 classrooms of 112 schools in 29 county-level units in mainland China in 2013–2014 and 2014–2015. Only the 2014–2015 CEPS collected information on student school travel time and mode, so we use the 2014–2015 CEPS. There are four types of questionnaires (students, parents, teachers, and school administrators) in the survey. This study uses student questionnaires that are completed by students in the classroom, and all variables used are self-reported by the students. After excluding the sample of boarding students, the final sample includes 6,353 eighth-grade students,[1] ranging in age from 12 to 19, with a mean age of 14.03 and a standard deviation of 0.79.

2.2. Outcomes variables

We examine adolescents' health across different domains (Table 1), ranging from subjective health to sickness absence.

Subjective health. The widely used subjective health measure is self-rated health, which was measured by the question 'Which one of the following best describes your general health condition at present'. Responses were five options: 1 = very poor, 2 = not very good, 3 = moderate, 4 = good, and 5 = very good. The second variable is mental stress, measured through a set of 10 questions derived from the extended version of the Patient Health Questionaire-9 (35). The question was 'How often have you felt (1) depressed (2) unfocused (3) unhappy (4) boring (5) could not work hard (6) sadness (7) tension (8) worry (9) something wrong will happen (10) too energetic and inattentive in class in the past 7 days?'. And each question had 5 options: 1 = never, 2 = seldom, 3 = sometimes, 4 = often, and 5 = always. We summed up the 10 emotional indicators with a value range of 0–50 (Cronbach's α coefficient = 0.912), and a higher score means worse mental health.

Physical health. The first measure of physical adolescents' health is body mass index (BMI), which is estimated using the standard equation (weight [kg]/height [m]^2). Age- and gender-specific BMI z-scores were calculated based on the guidelines "overweight and obesity criteria for school-age children and adolescents" published by the Chinese National Health Commission in 2018[2], participants were categorized as healthy and overweight/obese (Healthy weight = 1, overweight/obese = 0). The second physical health measure is how often someone called in sick (cold, fever, cough, diarrhea) during the last year. Responses included never (1), seldom (2), often (3). The third measure is whether the adolescent has ever had one of the six serious illnesses (kidney, lung, heart, brain, upper limb fracture, lower limb fracture). Each question had two options: yes (1) and no (2).

Sickness absence. We also use adolescents' sickness absence as a health outcome, and the assessment is based on a self-reported measure of the number of days absent due to sickness in the previous year.

2.3. Exposures variables

Students in CEPS 2014–2015 were asked about their school travel mode. The question was: 'what mode do you usually use from home to school?' Respondents choose one of the 12 options: walking, bicycle, motorbike, electric bicycle, city bus, coach, private car, train, boat, underground, or other commuting modes.

TABLE 1 Description of the variables.

Variables	Definition
Dependent variable	
Cycling to school	Cycling to school = 1
Independent variables	
Self-reported health	Very poor = 1 to very good = 5
Mental stress	Score scale from 1 to 50
BMI	Healthy weight = 1, overweight/obese = 0
Kidney disease	Yes = 1
Lung disease	Yes = 1
Heart disease	Yes = 1
Brain disease:	Yes = 1
Upper limb fracture	Yes = 1
Lower limb fracture	Yes = 1
Sickness frequency	Never = 1, seldom = 2, often = 3
Sickness absence	Days in sick during the last year
Control variables	
Gender	Male = 1
Only-child	Only-child = 1
Hukou	Rural = 1
Migrant children	Yes = 1
Physical activity	Min/week
Commute times	Number of minutes from home to school
Father's education	Year
Mother's education	Year
Family socioeconomic	Poor = 1 to very rich = 5
Residential district	Central area = 1, outskirts =2; rural =3
School rank	5-point Likert scale
Teacher's education	The number of teachers has obtained a bachelor's degree
School type	Public school = 1
County fixed effect	28 dummy variables

We are transforming commuting mode into a binary variable which equals 1 for adolescents bicycling to school and 0 otherwise. Based on this survey question, we created three dummy variables. One is a dummy variable that indicates whether a participant commutes by bicycle, and it takes the value of 1 if they commute by bicycle, and 0 otherwise. The second dummy variable indicates whether the participant bicycles or walks to travel, with a value of 1 for bicycle commuters and 0 for walkers. Lastly, the third dummy variable indicates whether the participant commutes by bicycle or passively, taking the value of 1 for bicycle commuters and 0 for passive commuters.

2.4. Covariates

The control variables in this study were roughly divided into three types.

1 In China, elementary schools cover grades 1–6 (ages 6–12); middle schools cover grades 7–9 (ages 12–16). 99.68% of the participants in this study were students between the ages of 12 and 16.

2 http://www.nhc.gov.cn/wjw/pqt/201803/a7962d1ac01647b9837110bfd2d69b26.shtml

Individual-level variables include gender (male = 1), only-child (yes = 1), Hukou[3] (Chinese household registration system, rural = 1), migrant status (yes = 1), commute duration, and physical activity. The commute duration was measured by the following question: How long does it usually take you to travel from home to school (minutes)? Physical activity was measured based on the student's self-reported time spent exercising in a week (minutes). The question asked 'The amount of time you spend on physical activity: [__] days per week, [__] minutes per day,' and the total number of exercise hours per week was calculated by multiplying the number of exercise days per week by the number of exercise hours per day.

Family background variables include parental education, socioeconomic status, and residential district. A student's parental education was measured by the number of years for which his or her parents had been educated. Family socioeconomic status was measured by asking the question 'What do you think of your family's current economic condition?.' Response options were: 1 = very poor, 2 = not very good, 3 = moderate, 4 = rich, and 5 = very rich. Residential districts were classified into three categories (1 = central area, 2 = outskirts area, 3 = rural area).

At the school level, indicators include type (public school = 1), ranking, and teacher education. It was requested that school administrators report a school's local ranking on a scale ranging from 1 (lowest) to 5 (highest). Teachers' education level is determined by how many of them have a college degree.

Moreover, traffic conditions, geography, or weather conditions may also affect the health benefits of cycling. Therefore, we included county fixed effects in the model to control for the effects of unobservable environmental factors.

2.5. Statistical model

We use propensity score matching (PSM) to explore the causal effects. The approach is to construct a synthetic control group and compare the bicycling outcomes of this group to the treatment group (41). Our PSM analysis consists of three steps. First, we predict propensity scores for every student using a logit model controlling all the covariates as mentioned above (42). Second, every treated student is matched to a controlled child, ensuring the two are as alike as possible apart from the commuting mode. To estimate the impact of bicycling on child health, we matched bicycle commuters with non-bicycle commuters based on socioeconomic and demographic characteristics at the individual, household, and county levels. Also, using the same control variables, we matched bicycle commuters with passive commuters or walkers. We use radius matching to estimate the causal effects, then use the neighbor and kernel matching for the robustness check. Third, the average treatment effects of bicycling can be computed as:

$$\mathrm{ATT} = \mathrm{E}\left(Health_{1i} - Health_{0i} | Bicyling_{i}\right)$$
$$= \mathrm{E}\left(Health_{1i} | Bicyling_{i} = 1\right) - \mathrm{E}\left(Health_{0i} | Bicyling_{i} = 0\right).$$

ATT represents the average treatment effects of bicycling on health. $Bicyling_i$ is a binary variable, reflecting whether the student i bicycling to school. $Health_{1i}$ refers to the health outcomes of the bicyclist, and $Health_{0i}$ is the i's health with other commute modes.

3. Results

3.1. Descriptive statistics

As shown in Table 2, 21% of Chinese adolescents bicycled to school. Regarding subjective health, students who biked to school had better self-rated health and less mental stress than those who commuted by other modes. In terms of physical health, there was little difference in BMI among those with different commute modes. Bicycle commuters were less likely to suffer from kidney, lung, heart, and brain disease but had a higher probability of upper and lower extremity fractures. Moreover, bicycle commuters reported fewer sick days than non-bicycle commuters. Significant differences were also found in the other characteristics of adolescents between the treatment and control groups. A sample selection bias may result from comparing the two groups directly before matching. This bias indicates that the difference in health between the two groups may not only result from changes in commuting patterns, but may also arise from individual or household characteristics. Our choice of PSM for causal inference was primarily motivated by this consideration.

3.2. Benchmark results

We used a logit model to estimate the likelihood of bicycling to school using all the covariates, and the estimated coefficients were saved as the propensity scores. As shown in Table 3, the estimated values confirm that the covariates significantly affect the likelihood of bicycling. Boys, non-only child, and rural area students are more likely to bicycle to school (all $p < 0.001$). The ethnic, commute time, and school-level factors are also related to the travel mode.

Next, we conduct a balance check to ensure that samples are well-balanced. Table 4 and Figure 1 show that all variables' standardized deviation (% bias) after matching was less than 5%. No systematic difference is found between the treatment and control groups, which means the parallel hypothesis[4] is satisfied and the covariate balance is met.

Then, we used caliper matching for estimation, and the neighbor and kernel matching methods for robustness testing, and the results obtained by the three methods were generally consistent. As shown in Table 4, we found a significant positive effect of bicycling to school on students' subjective health, including enhanced self-rated health (ATT = 0.06, SE = 0.04, $p < 0.05$), reduced mental stress (ATT = −0.73, SE = 0.33, $p < 0.01$). Regarding physical health, we found that bicycle commuters had a healthier weight (ATT = 0.03, SE = 0.15, $p < 0.01$) and

3 A person's hukou is determined by the hukou of his or her parents and the place in which they reside. Agricultural and non-agricultural are the two types of hukou. There are different opportunities and restrictions associated with different hukou (35, 36).

4 The parallel hypothesis is that there is no significant difference between the treatment and control groups in the matching variables; that is, the difference in the health outcomes between the two groups is entirely caused by the commute mode.

TABLE 2 Descriptive statistics.

Variable	Bicycle commuters					Non-bicycle commuters				
	Mean	*N*	SD	Min	Max	Mean	*N*	SD	Min	Max
Independent variables										
Self-reported health	3.936	1,321	0.922	1	5	3.883	4,982	0.940	1	5
Mental stress	21.232	1,301	8.234	10	50	21.536	4,917	8.337	10	50
BMI	0.867	1,295	0.340	0	1	0.886	5,026	0.318	0	1
Sickness absence	1.738	1,304	7.089	0	123	1.881	4,908	10.605	0	365
Kidney disease	0.004	1,327	0.061	0	1	0.007	5,026	0.085	0	1
Lung disease	0.038	1,327	0.190	0	1	0.046	5,026	0.210	0	1
Heart disease	0.006	1,327	0.077	0	1	0.008	5,026	0.090	0	1
Brain disease:	0.004	1,327	0.061	0	1	0.008	5,026	0.088	0	1
Upper limb fracture	0.063	1,327	0.242	0	1	0.057	5,026	0.232	0	1
Lower limb fracture	0.033	1,327	0.179	0	1	0.029	5,026	0.169	0	1
Sickness frequency	1.938	1,310	0.469	1	3	0.010	2,623	0.097	1	3
Control variables										
Gender	0.641	1,303	0.480	0	1	0.486	4,960	0.500	0	1
Only child	0.487	1,310	0.500	0	1	0.558	4,959	0.497	0	1
Hukou	0.290	1,327	0.454	0	1	0.352	5,026	0.478	0	1
Ethnic	0.941	1,323	0.236	0	1	0.915	5,007	0.279	0	1
Migrant children	0.809	1,309	0.393	0	1	0.783	4,936	0.412	0	1
Commute time	15.597	1,327	10.550	1	155	17.973	5,026	15.307	0	180
Physical activity	51.421	1,295	51.529	0	700	47.024	4,921	44.770	0	999
Father's education	10.951	1,284	3.322	0	19	11.159	4,845	3.209	0	19
Mother's education	10.400	1,277	3.435	0	19	10.640	4,826	3.522	0	19
Family socioeconomic	2.853	1,282	0.533	1	5	2.893	4,838	0.565	1	5
Residential district	1.878	1,277	0.837	1	3	1.826	4,790	0.847	1	3
School rank	4.096	1,327	0.820	1	5	3.983	5,026	0.841	1	5
School type	0.976	1,327	0.153	0	1	0.975	5,026	0.156	0	1
Teacher's education	79.163	1,279	43.251	0	195	84.064	4,881	41.733	0	195

TABLE 3 Propensity score (cycling to school vs. non-bicycling).

Variable	Coef.	Std. Err.	*p*-value	95% CI
Gender	0.633	0.072	0.000	0.493, 0.774
Only child	−0.382	0.079	0.000	−0.537, −0.226
Hukou	−0.286	0.081	0.000	−0.445, −0.127
Ethnic	0.410	0.144	0.004	0.129, 0.692
Migrant children	0.212	0.094	0.024	0.028, 0.397
Commute time	−0.015	0.003	0.000	−0.021, −0.009
Physical activity	0.001	0.001	0.179	0.000, 0.002
Father's education	0.005	0.015	0.759	−0.025, 0.034
Mother's education	−0.016	0.014	0.260	−0.045, 0.012
Family socioeconomic status	−0.095	0.065	0.146	−0.222, 0.033
Residential district	−0.057	0.049	0.239	−0.152, 0.038
School rank	0.251	0.048	0.000	0.157, 0.344
School type	0.433	0.263	0.100	−0.082, 0.949
Teacher's education	−0.004	0.001	0.000	−0.006, −0.002

were significantly less likely to have brain disorders (ATT = −0.01, SE = 0.00, $p < 0.01$). No significant relation is found among bicycling, sickness absence, and sickness frequency.

As shown in Table 5, we compared the bicycling group with both the walking and the non-active travel groups separately. There is still evidence that cycling generates beneficial outcomes for students. Cycling to school resulted in higher self-rated health (ATT = −0.12, SE = 0.05, $p < 0.001$) and a lower mental stress score (ATT = −0.82, SE = 0.37, $p < 0.01$) than walking. Physically, students who bicycled to school were less likely to be absent from school (ATT = −1.29, SE = 0.46, $p < 0.001$) and had kidney (ATT = −0.01, SE = 0.00, $p < 0.001$) and brain diseases (ATT = −0.01, SE = 0.00, $p < 0.01$). However, we did not find a significant difference in health outcomes between cycling and other non-active modes of transportation.

There is a massive gap in economic development, transportation, and living environment between urban and rural areas in China. Therefore, this paper conducted a subsample regression based on students' home locations. Table 6 shows that bicycling to school did not significantly affect students' health in urban centers, while bicycle commuters living in the urban fringe (ATT = −1.72, SE = 0.77, $p < 0.01$), and rural areas (ATT = −1.33, SE = 0.65, $p < 0.01$) had lower

TABLE 4 Parallel hypothesis in estimating the ATT of bicycling to school on the health.

Variable	Match	Treated	Control	%bias	%reduct	*t*	*p*>*t*
Gender	U	0.63	0.48	31.30		9.18	0.00
	M	0.63	0.64	−2.90	90.80	−0.69	0.49
Only child	U	0.48	0.57	−18.20		−5.40	0.00
	M	0.48	0.49	−1.30	92.80	−0.31	0.76
Hukou	U	0.29	0.37	−16.80		−4.88	0.00
	M	0.29	0.30	−1.10	93.60	−0.26	0.79
Ethnic	U	0.94	0.92	9.70		2.74	0.01
	M	0.94	0.93	2.20	77.00	0.56	0.58
Migrant children	U	0.82	0.79	6.80		1.99	0.05
	M	0.82	0.82	−1.50	77.60	−0.37	0.71
Time	U	15.49	17.86	−18.00		−4.91	0.00
	M	15.50	15.72	−1.70	90.40	−0.47	0.64
Exercise_time	U	50.63	47.20	7.40		2.21	0.03
	M	50.46	51.49	−2.20	69.80	−0.47	0.64
Father's_edu	U	10.90	11.19	−9.00		−2.67	0.01
	M	10.90	10.93	−0.90	90.50	−0.20	0.84
Mother's_edu	U	10.26	10.67	−11.80		−3.48	0.00
	M	10.26	10.30	−1.10	91.00	−0.25	0.80
Fame_con	U	2.85	2.90	−8.90		−2.61	0.01
	M	2.85	2.85	0.10	99.10	0.02	0.99
Resid_dis	U	1.89	1.82	7.60		2.26	0.02
	M	1.88	1.89	−1.10	85.50	−0.26	0.80
School_rank	U	4.10	4.00	11.30		3.32	0.00
	M	4.10	4.07	2.60	77.20	0.62	0.54
School_type	U	0.98	0.97	5.00		1.42	0.16
	M	0.98	0.98	−0.80	84.50	−0.20	0.84
Teacher_edu	U	79.55	85.18	−13.40		−4.01	0.00
	M	79.59	78.62	2.30	82.90	0.55	0.58

U, Unmatched; M, Matched.

mental stress. In addition, bicycle commuters in the urban fringe had a relatively lower probability of lower limb fractures (ATT = −0.03, SE = 0.01, $p < 0.01$). Moreover, bicycle commuters in rural areas are less likely to get kidney disease (ATT = −0.01, SE = 0.00, $p < 0.05$) and be absent on sick leave (ATT = −1.34, SE = 0.55, $p < 0.01$). In summary, we found that the health benefits of bicycle commuting were particularly pronounced for students in both urban edge and rural areas (Table 7).

4. Discussion

Based on data from the 2014–2015 China Education Panel Survey, this paper used propensity scores to design comparable treatment and control groups and then estimated the causal relationship between bicycling and students' multidimensional health. The main results indicate that bicycling to school positively affects both subjective and physical health. No significant relation is found among bicycling, sickness frequency, and sickness absence.

One key finding of this study is that bicycling to school positively affected students' subjective health compared with those who use other commute modes. First, bicycling can reduce students' mental stress, possibly because the bicycle commute allows students to be in close contact with nature and the outside environment, stimulating positive emotions and reducing anxiety (43). Previous research has found that bicycle commuting effectively reduces mental anxiety in adults (15–17, 44, 45), and this paper shows that this effect is also present in adolescents. In a study involving Swedish children (10–15 years of age), Westman et al. (46) directly assessed the emotional state of the children upon arriving at school. Also, the results indicated that children were more likely to experience a positive feeling when they traveled by bicycle. With nearly 30 million Chinese adolescents suffering from mental anxiety, our study may prove that promoting bike commuting is an effective intervention to enhance Chinese adolescents' mental health. Moreover, we also found that bicycling to school enhances students' self-rated health. Compared to mental stress, self-rated health is a comprehensive indicator (47). This paper shows that

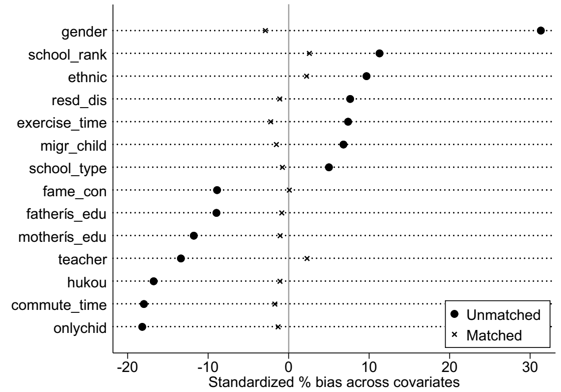

FIGURE 1
Propensity distributions of treated and control groups before and after matching.

TABLE 5 Effects of bicycling on adolescent health (bicycling vs. walking; bicycling vs. non-active commute).

Variable	Bicycling vs. walking			Bicycling vs. non-active commute		
	ATT	SE	T-stat	ATT	SE	T-stat
Self-report health	0.12***	0.05	2.86	−0.02	0.08	−0.21
Mental stress	−0.82**	0.37	−2.23	0.00	0.68	0.01
BMI	0.02	0.01	1.32	0.02	0.03	0.88
Sickness absence	−1.29***	0.46	−2.83	0.06	0.75	0.07
Kidney disease	−0.01***	0.00	−2.89	−0.00	0.01	−0.26
Lung disease	−0.00	0.01	−0.23	−0.01	0.02	−0.81
Heart disease	−0.00	0.00	−0.44	0.00	0.01	0.24
Brain disease	−0.01**	0.00	−2.37	−0.00	0.01	−0.32
Upper limb fracture	−0.01	0.01	−0.68	0.00	0.02	0.21
Lower limb fracture	−0.01	0.01	−1.08	−0.01	0.01	−058
Sickness frequency	−0.01	0.02	−0.33	−0.04	0.03	−0.96

ATT, Average Treatment Effect on the Treated; SE, Standard Error; T-stat, T-statistic; $^{**}p<0.01$; $^{***}p<0.001$.

mental stress and physical health may contribute to improving students' self-rated health.

This study also identifies a positive association between bicycle commuting and students' physical health. Notably, bicycle commuters were significantly less likely to suffer from brain diseases than the control group, and the probability of suffering from other diseases and frequency of illness were not affected. This finding further supports the mental health benefits of bicycling, as numerous studies have shown a correlation between mental stress and brain disease (48–50). Previous studies have shown that cycling for a prolonged period of time can improve adolescent BMI and reduce obesity (51, 52), we also found a positive relationship between bicycling to school and teenagers' BMI. Thus, teenagers who engage in cycling as a form of extracurricular exercise can also effectively improve their body mass index (53).

Moreover, school attendance is vital for students' academic performance and future development (54, 55), so we further investigated the relationship between bike commuting and students' sick leave absences. Previous studies have found that active commuting reduces sick leave absenteeism in adults (19, 20, 56), but we did not find this effect in adolescents.

Also, this study compares bicycling trips with walking and passive commuting. A previous study, based on survey data of adults at work, showed that those who regularly commuted to work by bicycle had better mental health than those who walked to work, but no physical benefits were evident (20). In contrast, the present study found mental and physical health benefits of bicycling among adolescents. This finding suggests that bicycling to school is a more effective way to improve students' health. The possible reason for this finding is that bicycling is more intensive than walking. Studies have shown that students whose home addresses are closer to school prefer to walk, and those who live a considerable distance away prefer to bicycle. When commuting times were similar between the two groups, students who commuted by bicycle traveled farther from home to school with the same amount of time. It meant that bicyclists did more exercise than those who commuted on foot (57). Although this study found more health benefits for bicycling than walking, we would like to emphasize that this does not negate the benefits of walking. This finding implies that, with regard to promoting students' active commuting, the government should prioritize bicycling over walking. Additionally, we found that cycling can also prevent kidney disease, which has been confirmed in previous medical research (58). Active commuting has been shown to benefit health in studies combining walking and biking (6, 18, 24, 26, 59). However, as compared to other passive modes of transportation, bicycling was not associated with significant differences in adolescents' health outcomes. This finding indicates that we should isolate the effects of bicycling trips from those of walking trips when studying active commuting among adolescents.

Finally, bicycling to school has health benefits for students living in rural and urban fringe areas, but not for those who live in urban centers. This finding was consistent with Lu (59), who conducted a cross-sectional study in Jiangsu, China, and found negative side effects of active commuting among urban residents than rural residents. One reason may be that with rapidly increasing motorization in China, traffic congestion is getting more serious, and those living in the city centers face more traffic and noise. The stress risks caused by a bad travel environment and air pollution may offset the potential positive effect of active commuting (60). We also found that bicycle commuting reduced the likelihood of sick leave absences among adolescents in rural areas. This finding may indicate that the benefits of bicycling to school are particularly beneficial for students living in rural areas.

5. Limitations

This study has limitations. First, we were only able to obtain relevant data up to the 2014–2015 wave, and changes in bicycle commuting and health output may have occurred since then. Scholars may continue to advance the research as new rounds of survey data

TABLE 6 Effects of bicycling on adolescent health (bicycling vs. non-bicycling).

Variable	Radius matching			Neighbor matching			Kernel matching		
	ATT	SE	T-stat	ATT	SE	T-stat	ATT	SE	T-stat
Self-report health	0.06*	0.04	1.71	0.07*	0.04	1.81	0.07*	0.04	1.75
Mental stress	−0.73**	0.33	−2.18	−0.77**	0.37	−2.08	−0.72**	0.34	−2.16
BMI	0.03**	0.15	1.97	0.04***	0.02	−2.57	0.03	0.01	1.95
Sickness absence	−0.56	0.35	−1.61	−0.37	0.40	−0.93	−0.56	0.35	−1.59
Kidney disease	−0.01	0.00	−1.39	−0.00	0.00	−1.33	−0.01	0.00	−1.38
Lung disease	−0.01	0.01	−1.15	−0.01	0.01	−1.13	−0.01	0.01	−1.15
Heart disease	−0.00	0.00	−0.35	−0.00	0.00	−0.43	−0.00	0.00	−0.34
Brain disease	−0.01**	0.00	−2.26	−0.01**	0.00	−2.15	−0.01**	0.00	−2.29
Upper limb fracture	0.00	0.01	0.50	0.01	0.01	0.63	0.00	0.01	0.51
Lower limb fracture	−0.00	0.01	−0.07	−0.00	0.01	−0.35	−0.00	0.01	−0.13
Sickness frequency	−0.01	0.02	−0.61	−0.01	0.02	−0.51	−0.01	0.02	−0.64

ATT, Average Treatment Effect on the Treated; SE, Standard Error; T-stat, T-statistic; $*p<0.05$; $**p<0.01$; $***p<0.001$.

TABLE 7 Effects of bicycling on adolescent health in different regions.

Variable	Center			Fringe			Rural		
	ATT	SE	T-stat	ATT	SE	T-stat	ATT	SE	T-stat
Mental stress	0.25	0.66	−0.38	−1.72**	0.77	−2.24	−1.33**	0.65	−2.04
Self -report	0.07	0.07	0.90	0.04	0.09	0.46	0.07	0.08	0.92
BMI	0.00	0.02	0.21	−0.01	0.01	−0.58	−0.06	0.06	−1.04
Sickness frequency	0.03	0.04	0.72	0.03	0.04	0.92	0.01	0.04	0.34
Kidney disease	−0.00	−0.00	−0.63	−0.00	0.01	−0.19	−0.01*	0.00	−1.66
Lung disease	−0.01	0.01	−0.78	−0.00	0.01	−0.16	0.00	0.01	−0.02
Heart disease	−0.00	0.00	−0.21	−0.00	0.00	−0.31	0.00	0.00	0.46
Brain disease:	−0.00	0.00	−0.65	−0.01	0.01	−1.16	−0.00	0.01	−0.61
Upper limb fracture	0.02	0.02	1.31	−0.01	0.02	−0.41	0.00	0.01	0.17
Lower limb fracture	0.01	0.01	0.72	−0.03**	0.01	−2.17	0.00	0.01	0.13
Sickness absence	0.13	0.96	0.13	0.03	0.38	0.08	−1.34**	0.55	−2.44

ATT, Average Treatment Effect on the Treated; SE, Standard Error; T-stat, T-statistic; $*p<0.05$; $**p<0.01$.

become publicly available in the future. Second, due to data limitations, this study cannot cover detail of students' commuting variables. Regarding commuting mode, we do not know the bicycling frequency and cannot observe whether there is a change in transportation mode, all of which may influence adolescents' health. For example, a study by Ma et al. (16) investigated the relationship between cycling frequency and health, and found that only regular cycling reduced mental stress and increased life satisfaction, while cycling occasionally had no health-promoting effects found for those who cycled occasionally. Third, the health-related data in this study were derived from students' self-reports, which may have some measurement bias compared to objective measurements. To improve the validity of the measures, future studies could collect objective data on student commutes and health from various perspectives. Fourth, a propensity score analysis can only partially overcome the omitted variable problem and cannot address reverse causality, and a longitudinal study is still needed to determine the causal association between bicycling and health outcomes. Finally, there may be other benefits of bicycle commuting, such as social dimensions, economic aspects, etc. that needs further discussion.

6. Implications

Adolescents' health can be influenced by school travel mode, policymakers need to learn about this relationship to motivate and enhances adolescents' wellbeing. First, this study shows that bicycling has more health benefits than walking. Based on this finding, the government should consider bicycling as an effective health promotion intervention than walking when it promotes active commuting among students. Policymakers also should deliver knowledge about the benefits of bicycling to parents and adolescents. Further, cities should improve bicyclists' infrastructure, making active transport more appealing so that young people can experience those health benefits. Finally, we found that bicycle have a positive effect on improving the health of urban fringe and rural students. However, due to economic poverty, many families in rural areas cannot afford a bicycle. Thus, there should be adequate financial investments in rural areas in planning and management.

7. Conclusion

This study examines the effects of bicycling to school on various health outcomes among adolescents. Using national-level data from Chinese school-aged children (12–19 years of age). We found that bicycling to school has a positive effect on both subjective and physical health. Bicycling to school was associated with higher self-rated health, a healthier weight, and lower mental stress levels, as well as a lower risk of developing a brain disease. Additionally, we compared the bicycling group with both the walking and non-active travel groups separately. Compared with walking, cycling to school resulted in a higher self-rated health score and a lower mental stress score. Physically, students who bicycled to school were less likely to be absent from school and had kidney and brain diseases. However, we did not find a significant difference in health outcomes between cycling and other non-active modes of transportation.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

Data collection was approved by the Ethics Committee of Renmin University of China, and each participant was informed of the purpose of this research. The participation of each participant in the study was voluntary, and they were assured that their privacy would be strictly protected.

Author contributions

PD performed the statistical analysis and drafted the manuscript. CD critically revised and helped to draft the manuscript. SF helped perform the analysis with constructive discussions. All authors designed the protocol for this study, read, and approved the final manuscript.

Funding

This research was funded by the National Natural Science Foundation of China (grant number 71871131) and the Fundamental Research Funds for the Central Universities (grant number CXJJ-2021-340).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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TYPE Original Research
PUBLISHED 23 May 2023
DOI 10.3389/fspor.2023.1113687

OPEN ACCESS

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RECEIVED 01 December 2022
ACCEPTED 02 May 2023
PUBLISHED 23 May 2023

CITATION
Pesola AJ, Esmaeilzadeh S, Hakala P, Kallio N, Berg P, Havu M and Rinne T (2023) Sensitivity and specificity of measuring children's free-living cycling with a thigh-worn Fibion® accelerometer.
Front. Sports Act. Living 5:1113687.
doi: 10.3389/fspor.2023.1113687

Sensitivity and specificity of measuring children's free-living cycling with a thigh-worn Fibion® accelerometer

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Objective: Cycling is an important part of children's active travel, but its measurement using accelerometry is a challenge. The aim of the present study was to evaluate physical activity duration and intensity, and sensitivity and specificity of free-living cycling measured with a thigh-worn accelerometer.
Methods: Participants were 160 children (44 boys) aged 11.5 ± 0.9 years who wore a triaxial Fibion® accelerometer on right thigh for 8 days, 24 h per day, and reported start time and duration of all cycling, walking and car trips to a travel log. Linear mixed effects models were used to predict and compare Fibion-measured activity and moderate-to-vigorous activity duration, cycling duration and metabolic equivalents (METs) between the travel types. Sensitivity and specificity of cycling bouts during cycling trips as compared to walking and car trips was also evaluated.
Results: Children reported a total of 1,049 cycling trips (mean 7.08 ± 4.58 trips per child), 379 walking trips (3.08 ± 2.81) and 716 car trips (4.79 ± 3.96). There was no difference in activity and moderate-to-vigorous activity duration ($p > .105$), a lower cycling duration (–1.83 min, $p < .001$), and a higher MET-level (0.95, $p < .001$) during walking trips as compared to cycling trips. Both activity (–4.54 min, $p < .001$), moderate-to-vigorous activity (–3.60 min, $p < .001$), cycling duration (–1.74 min, $p < .001$) and MET-level (–0.99, $p < .001$) were lower during car trips as compared to cycling trips. Fibion showed the sensitivity of 72.2% and specificity of 81.9% for measuring cycling activity type during the reported cycling trips as compared to walking and car trips when the minimum required duration for cycling was less than 29 s.
Conclusions: The thigh-worn Fibion® accelerometer measured a greater duration of cycling, a lower MET-level, and a similar duration of total activity and moderate-to-vigorous activity during free-living cycling trips as compared to walking trips, suggesting it can be used to measure free-living cycling activity and moderate-to-vigorous activity duration in 10–12-year-old children.

KEYWORDS
cycling, walking, active travel, accelerometer, energy expenditure, METS (metabolic equivalent of tasks), moderate-to-vigorous activity

1. Introduction

Children's daily physical activity accumulates from several sources, including school time, active hobbies, free play, and active travel. From these, active travel can form 20%–40% of daily moderate-to-vigorous physical activity, given it is a frequent, habitual part of daily living (1, 2). The most common forms of active travel are walking and cycling, with cycling being particularly common in Northern Europe and Scandinavian countries (3).

Cycling is more consistently associated with health outcomes, such as lower adiposity and cholesterol concentration, and a higher physical fitness, when compared to walking in children and adolescents (4–8). One possible reason is that habitual cycling is more intense as compared to walking (9). Measuring free-living cycling, and physical activity level during cycling, is important to better emphasize these benefits, and to promote cycling as part of children's physical activity habits and public health.

Device-based methods, primarily accelerometers, have improved free-living physical activity and moderate-to-vigorous physical activity measurement accuracy, but measuring free-living cycling remains a challenge. This is mainly because device impacts during cycling at typical wear locations like leg, trunk, or wrist, are minimal and not in proportion to the energy expenditure of cycling (10–13). Accordingly, children's free-living cycling energy expenditure and moderate-to-vigorous activity is under-estimated when using methodology assuming a linear association between accelerometer-counts and energy expenditure (14, 15). Validity is improved considerably when cycling is measured with multiple accelerometers or an accelerometer accompanied with other sensor, like heart rate, temperature, pressure, or GPS sensor (16–20). However, using these methods in larger samples and during free-living can be burdensome for the researchers and participants. Another approach for a single accelerometer system is to first recognize physical activity type (including, e.g., sitting, standing, walking and cycling), and then estimate energy expenditure for each of these activity types (21, 22). Since this method does not assume a linear association between accelerometer output and energy expenditure, the cycling energy expenditure estimate is possibly more valid as compared to estimates from more traditional methods.

Most of the studies validating different devices and analytical decisions in relation to cycling intensity have been performed in controlled laboratory conditions, where laboratory-grade criterion measures can be used. Given children's free-living activities are often sporadic and omnidirectional, the methods used to estimate their activities should be validated in free-living conditions (23). Given the mentioned challenges in measuring free-living cycling, proper criterion measures are also less available. Active travel habits are often measured with questionnaires or travel logs, which provide excellent individual-level validity for travel mode and are easier to use in larger samples as compared to device-based measures, like GPS sensors (24). Therefore, comparing device-measured physical activity during questionnaire-based travel modes can provide a possibility to evaluate the relative physical activity level between these travel modes in free-living conditions.

The first aim of this study was to quantify cycling duration, moderate-to-vigorous physical activity duration and metabolic equivalent of task (MET) level measured with a thigh-worn Fibion® accelerometer during free-living cycling trips, and to compare these to free-living walking (active reference) and car (sedentary reference) trips in 10–12-year-old children. The second aim was to study the sensitivity and specificity of Fibion® in measuring cycling during the cycling trips as compared to the walking and car trips.

2. Methods

Data was collected in FREERIDE project from 10 to 12-year-old children living in two South-Eastern Finnish cities, Mikkeli and Kouvola (25, 26). After receiving permission to recruit participants through schools, children and their parents were contacted through 11 primary schools in Mikkeli and 10 primary schools in Kouvola. Study info sheets and informed consent forms were delivered to teachers and taken to homes via children. The participants for the present study were a total of 160 children who returned informed consent signed by their parents and were willing to participate based on oral consent from themselves ($n = 461$), provided accelerometer and travel log data from same days ($n = 365$), and finally, reported any cycling, walking or car trip and had accelerometer data from these time segments ($n = 160$). Study protocol was approved by Aalto University Research Ethics Committee on 10th October 2019 and data collection was done in Spring 2021 during snow-free time.

Questionnaire data was collected at schools during one lesson totaling approximately 45 min, and accelerometer and travel log data was collected during the following 8 days. At school, the researcher first demonstrated how to complete the questionnaires, and children filled in the questionnaire on internet browser, while the researcher was available for questions and assistance. Subsequently, the researcher assisted in wearing the accelerometers, delivered extra medical adhesives and travel logs, and gave instructions for these measurements. This was done for one child at a time, either during recess or the next lesson.

2.1. Measurements

Questionnaire included questions about background variables and visits to different destinations and travel modes, which are reported elsewhere (25, 26).

Travel log was developed based on Helsinki region travel survey and was tailored for the purposes of the present study (27). Children were asked to report the exact start time of each trip, trip destination (school, home, organized sports, other organized activity, play, friends, shopping, or other), the primary travel mode (walk, bike, car, bus or school taxi, walking or cycling to transit stop, skate or scoot, other), as well as duration of the trip (categorical variable: less than 5, 5–15, 16–30, 31–45 min, and more than 45 min). For the purposes of accelerometer measurement, the children were also asked to report their waking up time, time when going to sleep, any non-wear periods, as well as whether the day was not a typical day (e.g., because being sick). A sample travel log is presented in **Supplementary Material**.

Accelerometer Children were wearing a Fibion® device (20 g, $L = 30$ mm, $W = 32$ mm, $T = 10$ mm; Fibion Inc, Jyväskylä, Finland) for 8 days, 24 h per day. The device was attached on the centerline of the anterior side of the thigh, one third from the proximal end, and secured in a waterproof covering with medical adhesive tape. The Fibion® device measures raw acceleration on three axes with an internal sampling rate of 12.5 Hz. The Fibion® device has no buttons or display and can operate for around 30 days on full charge condition. Fibion® is valid in estimating moderate-to-vigorous physical activity and energy expenditure against indirect calorimetry, which were the variables used in the present study (21, 22) Moreover, Fibion® has an overall accuracy of 85%–89% in detecting different activity types, with high accuracy (94%–100%) for detecting prone and supine lying, sitting, and standing. Fibion® has good to excellent validity for measuring sedentary (sitting) and upright (standing and walking) time against the ActivPAL4 monitor (22). Similar to ActivPAL4, Fibion has poorer reliability for measuring free-living cycling duration (28). However, moderate-to-vigorous activity during cycling or sensitivity and specificity in measuring children's free-living cycling has not been investigated.

2.2. Outcomes

Cycling, walking and car trips were segmented from Fibion data based on start time and duration of each trip reported in the Travel log (**Supplementary Material**). These trip types were selected because they are common in children's everyday life. Walking serves as a reference trip type for cycling because walking is typically more accurately detected with thigh-worn accelerometers than cycling (28). Car serves as a passive reference for cycling, since car trips should be less active than any active trips, including cycling trips. Travel log may be prone to recall error and given the trip duration was asked as a categorical variable, the trip duration segmented based on the travel log likely includes also other activities than the active travel. However, we assume these errors are similar between travel modes, and therefore by estimating differences between these travel modes should effectively eliminate such errors.

Activity duration, Moderate-to-vigorous activity duration and *Cycling duration* were calculated as a sum over each trip segment.

Metabolic equivalent of tasks (METs) were calculated by dividing the Fibion-estimated total energy expenditure of each trip segment by resting energy expenditure estimated individually for each child (29).

2.3. Statistical analyses

Before further analysis data was checked for skewness, kurtosis, outliers and normality. The Shapiro-wilk test was used to assess the normality of data distribution. Package "lessR" was used to calculate the means of the variables and differences between them (i.e., independent samples *t*-test) (30). Linear mixed effects models were used to estimate and compare activity duration, moderate-to-vigorous activity duration (MVPA in the equation), cycling duration and METs during cycling trips as compared to walking and car trips. The interaction between travel modes according to their duration (factor) was used as the fixed variable and participant (accounting for several trips from each participant) was used as the random variable as below:

$$Activity\ model = lmer(Activity \sim Travel\ mode \times Duration + (1 + Travel\ mode \times Duration|Participant))$$

$$MVPA\ model = lmer(MVPA \sim Travel\ mode \times Duration + (1 + Travel\ mode \times Duration|Participant))$$

$$Cycling\ model = lmer(Cycling \sim Travel\ mode \times Duration + (1 + Travel\ mode \times Duration|Participant))$$

$$METs\ model = lmer(METs \sim Travel\ mode \times Duration + (1 + Travel\ mode \times Duration|Participant))$$

Packages "lme4" and "lmerTest" were used to perform linear mixed model and to get *p*-values, respectively (31, 32). To test if the models are significant or not, we used Likelihood Ratio Test (31). For this mean we compared our models with a null model by replacing fixed value with gender. Package "table1" and "sjplot" were used to export results to table format (33, 34). Packages "ggplot2" and "ggeffects" were used to get the marginal means and confidence intervals for the models (35, 36). Finally, package "Epi" was used to calculate the sensitivity and specificity between Fibion-measured cycling during reported cycling trips versus walking and car trips (37). Because children's activities are sporadic (23), we tested different time windows (between >0 and >50 s) for the minimum duration of cycling required (38–40). Statistical analyzes were done using RStudio Version R-4.1.2 for windows. Statistical significance was set at $p < 0.05$ (two-tailed).

3. Results

Participants were a total of 44 boys and 116 girls aged 11.5 years (**Table 1**). They reported a total of 1,049 cycling trips (mean 6.6 trips per child), 379 walking trips (mean 2.5 trips per child) and 716 car trips (mean 4.5 trips per child) and accumulated a total of 2 h of cycling, 0.8 h of walking, and 1.5 h of car trips per week without differences between the genders (**Table 1**).

Accumulation of accelerometer-measured physical activity before, during and after the segmented trips was visualized in **Figure 1** to visually confirm that the reported trip segments increase physical activity. **Figure 1** shows, that physical activity increases during cycling and walking trips, but decreases during car trips.

3.1. Linear mixed effects models

Linear mixed effects model results are presented in **Table 2** and estimated marginal means in **Figure 1B**. There was no difference in activity and moderate-to-vigorous activity duration during walking trips as compared to cycling trips. As expected, there was a lower cycling duration during walking trips compared to cycling trips

TABLE 1 Background and weekly trip characteristics by gender.

	All	Boys	Girls	p-value
	N = 160	N = 44	N = 116	
Age (years)	11.5 (0.88)	11.6 (0.91)	11.5 (0.87)	0.821
Height (cm)	153 (11.4)	153 (7.33)	154 (12.6)	0.695
Weight (kg)	47.3 (10.4)	47.5 (11.0)	47.2 (10.1)	0.878
Number of cycling trips per week	6.64 (4.80)	6.52 (4.29)	6.68 (4.99)	0.843
Cycling trip duration (h/week)	1.95 (1.42)	1.85 (1.15)	1.98 (1.52)	0.550
Cycling trip activity (h/week)	1.30 (1.08)	1.17 (0.89)	1.35 (1.14)	0.284
Cycling trip moderate-to-vigorous activity (h/week)	0.93 (0.81)	0.85 (0.65)	0.96 (0.86)	0.372
Number of walking trips per week	2.46 (2.85)	1.98 (2.26)	2.64 (3.03)	0.138
Walking trip duration (h/week)	0.79 (0.91)	0.67 (0.79)	0.84 (0.96)	0.239
Walking trip activity (h/week)	0.49 (0.64)	0.40 (0.56)	0.53 (0.67)	0.223
Walking trip moderate-to-vigorous activity (h/week)	0.40 (0.55)	0.31 (0.47)	0.43 (0.57)	0.154
Number of car trips per week	4.54 (4.04)	4.77 (3.69)	4.46 (4.18)	0.643
Car trip duration (h/week)	1.47 (1.33)	1.50 (1.18)	1.46 (1.39)	0.835
Car trip activity (h/week)	0.43 (0.45)	0.46 (0.40)	0.42 (0.46)	0.542
Car trip moderate-to-vigorous activity (h/week)	0.26 (0.30)	0.32 (0.30)	0.24 (0.30)	0.141

(−1.83 min, $p < .001$). Both activity (−4.54 min, $p < .001$), moderate-to-vigorous activity (−3.60 min, $p < .001$) and cycling duration (−1.74 min, $p < .001$) were lower during car trips as compared to cycling trips (Table 2).

Trip segment duration reported in the travel log affected the measured activity duration, such that activity, moderate-to-vigorous activity, and cycling duration were longer during 16–30 min trips and 31–45 min trips as compared to 5–15 min trips ($p < .001$, Table 2).

Likelihood Ratio Test showed a significant change of activity (Chisq = 246.85; $p < .001$), moderate-to-vigorous activity (Chisq = 204.51; $p < .001$) and cycling (Chisq = 124.75; $p < .001$) between travel modes. In other words, Fibion® can detect a difference in these variables when these three travel modes are considered.

MET-level was significantly lower during car trips (−0.99, $p < .001$), but significantly higher during walking trips (0.95, $p < .001$) as compared to cycling trips (Table 2). Trip segment duration had no influence on the measured MET-level, suggesting that travelling intensity did not change as a function of trip duration. Likelihood Ratio Test indicated a significant change of METs between travel modes (Chisq = 126.60; $p < 0.001$), meaning that Fibion® measures a difference in METs between cycling, walking, and travelling by car (Table 2).

3.2. Sensitivity and specificity

Table 3 shows the results of sensitivity and specificity between Fibion® reported cycling and diary reported cycling versus walking and car trips. The required minimum duration of cycling had an influence on the sensitivity and specificity. When minimum required cycling duration was 29 s or less, sensitivity was 72.2% and specificity 81.9%. When the minimum duration of cycling was increased, sensitivity decreased (down to 63.0% with >50 s required for cycling) and specificity increased (up to 91.1% with >50 s required for cycling). Therefore, a higher minimum duration for cycling can be used to increase specificity, but for better sensitivity, the minimum duration required for cycling should be less than 29 s per trip.

4. Discussion

The aim of this study was to investigate capability of a thigh-worn Fibion® accelerometer in estimating energy expenditure and physical activity during free-living cycling in 10–12-year-old children, which is a common challenge in device-based physical activity measurements. The main strength of this study is that we were able to analyze data from more than 2,144 free-living trips, including 1,049 cycling trips. The estimated differences between the travel modes showed that Fibion® captured more cycling, a lower MET-level, but a similar activity and moderate-to-vigorous activity duration during cycling trips as compared to walking trips. Because children's activity is often sporadic, the sensitivity and specificity were estimated by using different minimum duration criteria for measured cycling. The sensitivity and specificity were optimized when the minimum required duration for measured cycling was 29 s or less, but at a longer required cycling duration sensitivity decreased. This indicates the sporadic nature of children's free-living cycling and suggests that only a fraction of the cycling trip duration includes leg movement that the device recognizes as cycling. Despite previous studies have faced challenges in measuring physical activity during cycling using primarily waist-worn or wrist-worn devices, these results show that a thigh-worn accelerometer can be used to measure a similar activity and moderate-to-vigorous activity duration during free-living cycling trips as compared to walking trips.

4.1. Cycling has many health benefits, but physical activity during cycling is often underestimated

Free-living cycling is associated with a lower adiposity, a lower risk of cardiovascular diseases, a higher physical activity and a higher fitness in children and adolescents (4–8). Cycling is more beneficially associated with these outcomes as compared to other active travel modes, like walking (4–8). Yet, on many occasions physical activity during cycling has been significantly underestimated or rated as sedentary activity when using accelerometry (14, 15), even in controlled laboratory settings and compared to other activities such as walking (13). For this reason, several investigators have tried to find methods to measure cycling accurately and differentiate it from other activities.

In their validation study Herman Hansen et al. used a hip-worn ActiGraph in a sample of young adults during treadmill walking and ergometer cycling, and found no linear relationship between energy expenditure and activity counts during cycling. They reported that physical activity levels were underestimated by 73% during cycling when compared to walking (13).

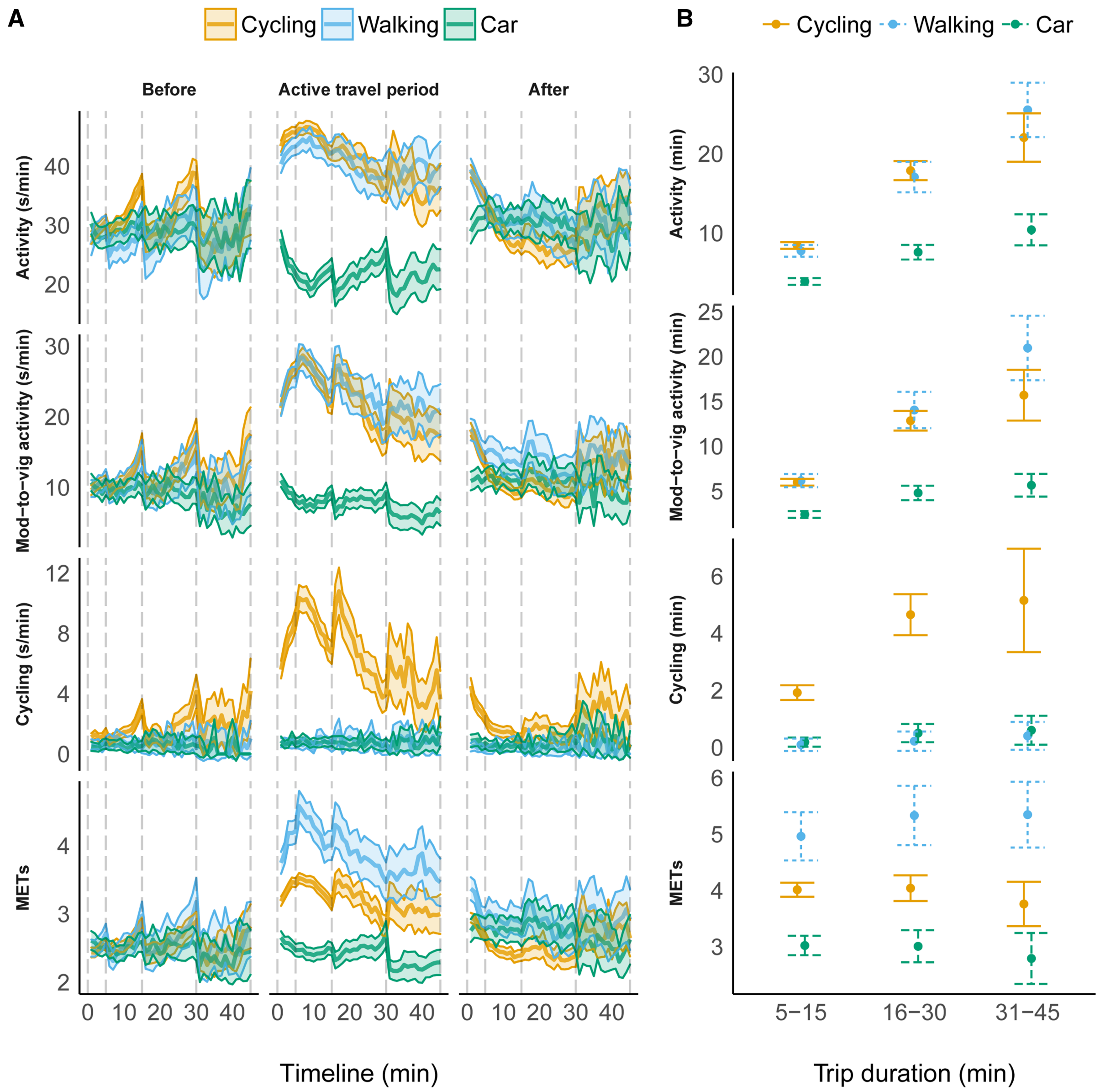

FIGURE 1
(A) Timeline of activity, moderate-to-vigorous activity, cycling, and METs before, during, and after the reported trip segments. The vertical dashed lines represent different travel log trip segment duration categories. (B) The estimated marginal means of activity, moderate-to-vigorous activity, cycling, and METs between travel modes during different trip segment durations.

Similarly, Troutman et al. reported a low reliability for laboratory measured cycling ($R = 0.05–0.75$) as compared treadmill walking ($R = 0.61–0.84$) using an ankle and hip-worn Mini-Logger accelerometers in a sample of 10–16 years old children and adolescents (41). They also reported a weak validity for cycling ($r = 0.06–0.15$) and moderate validity for walking ($r = 0.37–0.67$) (41). Jakicic et al. found a significant association between energy expenditure of various activities (i.e., walking, running, stepping, and sideboard exercise) measured by a triaxial waist-worn accelerometer (TriTrac-R3D) and indirect calorimetry in young adults (10). However, they observed no association for cycling (10). Tarp et al. quantified the underestimation of free-living cycling activity measured with a hip-worn accelerometer (Actigraph GT3X) in 11–14 years old children (15). They noticed that cycling to and from school is an important source of physical activity for children and contribute substantially to moderate-to-vigorous physical activity levels, yet the accelerometer measured only 2.5%–3.3% of moderate-to-vigorous activity measured with heart-rate-monitor during cycling (15). The same result was also observed by Evenson et al. who used two hip worn accelerometers (ActiGraph and Actical) to estimate different activities in 5–8 years old children (14). Although both oxygen uptake (VO_2) and heart rate were higher for stationary measured cycling than sedentary activities (e.g., watching a DVD, resting, and coloring) and walking they found that both accelerometers considered cycling as sitting/sedentary (14).

TABLE 2 Activity, moderate-to-vigorous activity, cycling and METs estimated with linear mixed models using cycling as the reference trip.

Predictors	Activity (minutes)			Moderate-to-vigorous activity (minutes)			Cycling (minutes)			METs		
	Estimates	CI	*p*	Estimates	CI	*p*	Estimates	CI	*p*	Estimates	CI	*p*
(Intercept)	8.43	8.00 to 8.85	**<0.001**	5.98	5.59 to 6.36	**<0.001**	1.92	1.66 to 2.17	**<0.001**	4.01	3.89 to 4.14	**<0.001**
Car (vs. cycling)	−4.54	−5.14 to −3.94	**<0.001**	−3.60	−4.14 to −3.05	**<0.001**	−1.74	−2.04 to −1.43	**<0.001**	−0.99	−1.20 to −0.78	**<0.001**
Walking (vs. cycling)	−0.67	−1.48 to 0.14	0.105	0.18	−0.65 to 0.98	0.656	−1.83	−2.16 to −1.49	**<0.001**	0.95	0.53 to 1.37	**<0.001**
Trip duration 16–30 min (vs. 5–15 min)	9.44	8.32 to 10.56	**<0.001**	6.86	5.80 to 7.90	**<0.001**	2.73	2.10 to 3.37	**<0.001**	0.03	−0.22 to 0.27	0.826
Trip duration 31–45 min (vs. 5–15 min)	13.61	10.64 to 16.58	**<0.001**	9.73	6.96 to 12.52	**<0.001**	3.24	1.48 to 4.97	**<0.001**	−0.26	−0.66 to 0.15	0.213
16–30 min car trip (vs. 5–15 min cycling trip)	−5.74	−7.29 to −4.20	**<0.001**	−4.44	−5.84 to −3.05	**<0.001**	−2.42	−3.16 to −1.68	**<0.001**	−0.04	−0.42 to 0.34	0.840
16–30 min walking trip (vs. 5–15 min cycling trip)	−0.15	−2.28 to 1.99	0.893	1.07	−1.18 to 3.32	0.350	−2.61	−3.35 to −1.87	**<0.001**	0.34	−0.33 to 1.01	0.318
31–45 min car trip (vs. 5–15 min cycling trip)	−7.08	−10.23 to −3.93	**<0.001**	−6.50	−9.50 to −3.50	**<0.001**	−2.81	−4.63 to −0.98	**0.003**	0.03	−0.60 to 0.66	0.930
31–45 min walking trip (vs. 5–15 min cycling trip)	4.16	−0.21 to 8.54	0.062	5.28	0.88 to 9.67	**0.019**	−2.91	−4.74 to −1.09	**0.002**	0.64	−0.13 to 1.40	0.102

Bolded values indicate statistical significance at $p < .05$.

TABLE 3 Sensitivity and specificity of Fibion-measured cycling during reported cycling trips (sensitivity) versus reported walking and car trips (specificity) using different minimum duration of Fibion-measured cycling.

Minimum required duration for cycling (s)	Sensitivity	Specificity	AUC
>0	72.4	81.8	0.77
>4	72.2	81.9	0.77
>9	72.2	81.9	0.77
>14	72.2	81.9	0.77
>19	72.2	81.9	0.77
>29	72.2	81.9	0.77
>34	69.7	83.8	0.77
>40	66.3	87.4	0.77
>50	63.0	91.1	0.77

AUC, area under the curve.

Together these findings illustrate that the typically used wear locations and linear estimation equations result in underestimated cycling energy expenditure.

4.2. Thigh-worn accelerometers can measure cycling movement better as compared to wrist or waist worn devices

In contrast to the previous studies by Tarp et al. and Evenson et al., we observed a significantly higher moderate-to-vigorous activity duration during cycling trips than car trips, and no difference between walking and cycling. This means that Fibion® can capture cycling moderate-to-vigorous activity better than devices and analysis methods used in previous studies (14, 15). This may be due to that the movement during cycling can be better captured with a thigh-worn accelerometer as compared to hip, wrist or waist worn accelerometer, given the impacts in these locations are disproportionally associated with the energy expenditure of cycling. More generally, thigh worn accelerometers have been shown to differentiate activity types (e.g., sitting, standing, cycling, walking, and running) and intensity of activities better than hip or wrist worn accelerometers (19, 28, 42–45). Another difference to previously used methods is that Fibion® applies a different energy expenditure estimation algorithm for different activity types, whereas many of the previous studies have relied on linear associations between impacts and energy expenditure, with evident challenges in relation to cycling (14, 15).

Despite similar moderate-to-vigorous activity, the estimated MET-level was higher during walking trips compared to cycling trips. This is a similar result as in a recent study performed by Lucernoni et al., who included a sample of young adults and found that four ActivPAL (two ActivPAL3 & two ActivPAL4) attached on thigh underestimated METs by 33%–60% during stationary cycling (46). Yet, it should be noted that the present study was performed in free-living settings instead of in a laboratory-controlled setting. Lucernoni et al. concluded that ActivPAL does not provide accurate estimation of METs during cycling in a controlled lab setting (46). One possible reason for the underestimation of cycling METs in the present study may be the fact that capturing of cycling activity using Fibion® is based on continuous pedaling, whereas free-living cycling can also include interruptions, e.g., in traffic lights or during freewheeling. Walking does not include similar freewheeling periods that are possible during cycling. Thus, stops or not pedaling will be recorded as sitting or standing, but not cycling. Furthermore, using higher gears during cycling results in slower pedaling frequency despite the higher resistance, and the movement during cycling does not necessarily correspond to the actual effort or energy expenditure of cycling. These aspects of cycling are difficult or impossible to capture with accelerometers, and therefore physiological monitors should be used when investigators need to measure the physiological intensity of cycling.

There are a few studies using a single thigh worn accelerometer for detecting different outdoor activities in children and adolescents in free living conditions, and the existing studies have used short and controlled activity conditions (i.e., 1.5–5 min for each activity). Brønd et al. included 96 children and adolescents and used a single thigh worn Axivity AX3 accelerometer for detecting sitting, standing, walking, running, and biking (16). They used an activity log to record activity start and end times. They observed a high sensitivity and specificity (~99%) for indoor measured activities such as sitting and standing but lower sensitivity and specificity (82.6%) for controlled, short, outdoor walking and running in both children and adolescents. They also reported sensitivity and specificity of ~85.8% and ~64.8% for identifying short controlled outdoor biking for children/adolescents and preschool children, respectively. They concluded that conducting a true free living validation study is challenging. In the present study we observed sensitivity of 72.2% and specificity of 81.9% (i.e., for time between 0 and 34 s), which is a similar magnitude to the study by Brønd et al., but included free-living, also longer duration, trips. Most recently, Bach et al. included 22 adults in their study and recorded their activities (e.g., sitting, standing, lying, walking, running, and cycling) during 1.5–2 h of free-living setting using direct video recording from chest, and dual accelerometers (Axivity AX3; worn on lower back and thigh) (47). Using machine learning methods, they observed that dual accelerometry can provide accurate estimation of free-living activities, but that a single thigh-worn accelerometer could also provide the same estimation. They reported sensitivity of 90% and specificity of 100% for the single thigh-worn accelerometer (47).

4.3. Sensor combinations can improve cycling intensity estimation but increase participant burden

One possible way for measuring free living physical activities (e.g., cycling) is using a combination of several devices at the same time, which allows for capturing not only activity types but also intensity, time, and distance of activities (48). For example, some studies suggested combination of both accelerometry, Global Positioning System (GPS) (49, 50) and heart rate (15) to measure cycling in children and adolescents. However, Brønd et al. argued that more complex algorithms or additional features (i.e., more accelerometers or other sensors) does not seem to help improving identification accuracy, but wear location and optimal selection of signal features may be more helpful (16). They suggested that more complex algorithms and increased amounts of features may increase the risk of overfitting leading to misclassification of some physical activity types in free living conditions. This applies especially to children whose activity behavior is sporadic and complex and thus difficult to capture (16). Thus, to achieve more accurate and better results, simple but robust methods such as single thigh-worn accelerometry should be considered.

In summary, while there are several recent studies using accelerometer/accelerometers combined with other sensors (e.g., heart rate, GPS) and analysing data with advanced statistical techniques, these high predictive values have been mainly provided models calibrated in laboratory conditions and are not necessarily reproducible in free-living conditions (51). This happens because of unseen and sporadic activities in free living conditions (43, 51, 52). Furthermore, it should be noted that using a combination of several sensors and statistical methods makes the process of measuring highly complex and difficult, in addition to the fact that this type of measurement is unfeasible in studies with large sample size and inconvenient for the participants (15, 52). Thus, it would be important to explore if a single sensor setup is capable in providing valid evaluations of key daily free-living activity types such as cycling (52). Such single-sensor measurements can be supplemented with, e.g., Ecological Momentary Assessment (EMA) (53), which is suggested to be more accurate than traditional self-report measures (54). Thigh-worn accelerometers are better in differentiating activity types and intensities compared to hip or wrist or waist-worn accelerometers (28, 45, 55). Although there are some studies showing excellent compliance with wrist-worn accelerometers in children (56), similar results have also been reported for thigh-worn accelerometers (17).

4.4. Strengths and limitations

The strength of this study is including a sample of children and their physical activity during several days in a free-living setting and using a simple method for estimation and evaluation of children's cycling behavior. The main limitation of the current study is using a travel log to capture the free-living cycling, walking and car trip segments. For example, the MET level during car trips was relatively high (~3 METs). Rather than being an indication of MET level while sitting in car, the overall car trip segment also includes events immediately before and after the car trip, like walking to and from the car. We aimed to minimize this error by comparing different travel modes, which we assume are prone to similar error, and as such, focusing on estimated differences, rather than estimated marginal means, is recommended. Similar self-report measures have been used in some previous studies (16) and such a simple method enabled capturing a relatively high number of free-living trip segments. Moreover, **Figure 1** shows that the reported trip segments included significantly more activity, moderate-to-vigorous activity, cycling, and a higher MET-level, as compared to segments recorded immediately before and after the reported trip segments. There was a higher number of girls than boys in the present study, which can be a real difference in their travel behavior but can also indicate under-reporting in boys. However, there were no differences in their overall weekly travel behavior suggesting that this bias, if any, should not affect the main results.

4.5. Conclusions

In conclusion, measuring physical activity during cycling has been difficult especially with hip, waist and wrist-worn accelerometers and due to relying on linear association between impacts and energy expenditure. Moreover, many of these studies have been conducted in controlled laboratory conditions, yet less data is available from free-living cycling. The present study quantified and compared activity, moderate-to-vigorous activity, cycling, and MET-level during more than 2,000 free-living trip segments in a sample of 10–12-year-old children. The thigh-worn Fibion® accelerometer measured a lower MET-level, but a similar activity and moderate-to-vigorous activity duration, and a higher cycling duration, during these reported cycling trips as compared to walking trips. Thigh-worn accelerometry can be used to measure free-living cycling activity and moderate-to-vigorous activity in children.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by Aalto University Research Ethics Committee. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

Funding: AJP, TR. Conception or design of the work: AJP, MH, PH, PB, TR. Data collection: PH, TR, NK. Data analysis and interpretation: AJP, SE, NK, MH. Drafting the article: AJP, SE. Critical revision of the article: All authors. All authors contributed to the article and approved the submitted version.

Funding

This work was supported by the Ministry of Education and Culture, Finland under Grants OKM/30/626/2019 and OKM/1097/626/2020. The funding agency had no role in study design; in the collection, analysis and interpretation of data; in the writing of the report; and in the decision to submit the article for publication.

Conflict of interest

AJP is a co-founder of Fibion Inc. MH has participated in developing the Fibion algorithms as a paid contractor.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fspor.2023.1113687/full#supplementary-material.

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frontiers | Frontiers in Sports and Active Living

TYPE Brief Research Report
PUBLISHED 26 May 2023
DOI 10.3389/fspor.2023.1146761

Check for updates

OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Physical Activity in the Prevention and Management of Disease, a section of the journal Frontiers in Sports and Active Living

RECEIVED 17 January 2023
ACCEPTED 20 March 2023
PUBLISHED 26 May 2023

CITATION
Kahlmeier S, Cavill N, Thondoo M, Rutter H, de Sa TH, Racioppi F and Gotschi T (2023) The Health Economic Assessment Tool (HEAT) for walking and cycling - experiences from 10 years of application of a health impact assessment tool in policy and practice.
Front. Sports Act. Living 5:1146761.
doi: 10.3389/fspor.2023.1146761

The Health Economic Assessment Tool (HEAT) for walking and cycling - experiences from 10 years of application of a health impact assessment tool in policy and practice

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Introduction: In recent years, walking and cycling have moved into the focus as promising approaches to achieve public health, sustainable transport, climate goals and better urban resilience. However, they are only realistic transport and activity options for a large proportion of the population when they are safe, inclusive and convenient. One way to increase their recognition in transport policy is the inclusion of health impacts of walking and cycling into transport economic appraisals.
Methods: The Health Economic Assessment Tool (HEAT) for walking and cycling calculates: if x people walk or cycle a distance of y on most days, what is the economic value of impacts on premature mortality, taking into account effects of physical activity, air pollution and road fatalities, as well as effects on carbon emissions. Different data sources were collated to examine how the HEAT in more than 10 years of existence, and to identify lessons learned and challenges.
Results: Since its launch in 2009, the HEAT has gained wide recognition as a user friendly, yet robust, evidence-based tool usable by academics, policymakers, and practitioners. Originally designed for use in Europe, it has since been expanded for global use.
Discussion: Challenges for a wider uptake of health-impact assessment (HIA) tools including active transport such as HEAT are the promotion and dissemination to local practitioners and policy makers also outside European and English-speaking regions and in low- and middle-income contexts, further increasing usability, and more generally the advancement of systematic data collection and impact quantification related to walking and cycling.

KEYWORDS
economic assessment, health impact assessment, cycling, walking, policy

10.3389/fspor.2023.1146761

1. Introduction

Over recent decades, a lack of physical activity has been recognized as a major determinant of ill health. Insufficient physical activity has been associated with many chronic diseases, including coronary heart disease, stroke, hypertension, cancer and type II diabetes, as well as excess body weight, poor mental health, and reduced independence in old age. Overall, more than 7% of all-cause and cardiovascular disease deaths and up to 8% of 13 major non-communicable diseases are attributable to insufficient physical activity (1). Globally, almost one out of four adults, and four out of five adolescents are not sufficiently active for good health (2, 3). An increasing number of studies have investigated health impacts from so-called “active travel”, i.e., regular cycling or walking for transport, including combined mobility with public transport. Demonstrated health benefits include a 10% reduction of premature mortality (4–6) and of metabolic risk factors for cardiovascular diseases (5, 6), the prevention of diabetes, some cancers and the reduction of cognitive function in older adults (7) and to some degree lower body weight (8, 9). During the COVID-19 pandemic, cycling and walking have also emerged as travel options that provide physical distancing required by public health measures while at the same time enabling people to remain physically active (10). As a result, many cities around the world have taken steps to promote walking and cycling (11, 12).

In recent years transport-related physical activity has moved into focus as a promising approach to reach parts of the population for whom sport is not amenable, attractive or affordable (13, 14). Both the “Eigth Investments that work” (15) and the Global Action Plan on Physical Activity include actions related to promoting safe, active transport (16). In 2021, the first European Masterplan for Cycling was adopted (17) and a new plan for walking promotion is under development. There is merit in increasing collaboration between the transport and health sectors to achieve transport goals such as reducing congestion or climate change (18, 19) as well as public health targets to reduce physical inactivity and disease burden (14, 20, 21). For example, in England and Wales, on average only 10 min per day are spent walking for transport, and less than 2 min for cycling. That more is possible beyond champion countries such as the Denmark or the Netherlands is seen in Switzerland, where over 20 min are spent for transport-related walking and 4.5 min for cycling each day (21). Such differences in transport behaviour translate into considerable public health impacts (14, 20, 21). In addition, evidence from 30 studies from Europe, as well as Australia, New Zealand and the United States of America shows that the benefits from physical activity clearly outweigh potential harm from air pollution or traffic crashes (22). A similar pattern is seen in evidence from some low- and middle-income settings, such as Brazil (23), Mauritius (24) or India (25).

For walking and cycling to present realistic transport alternatives for a large share of the population, they need to be safe and convenient (11, 13, 14, 16). Planning practice can draw from a wide portfolio of well-established infrastructure and traffic regulation measures to make active travel modes more palatable. However, the priority given to the promotion of active travel modes in transport planning varies widely, as differences exist between countries, cities, towns, and rural areas (18, 26). In addition, issues of inequity and social justice influence the relationship between transport and health by modifying the exposure and severity of health effects and outcomes (27, 28), further stressing the need to estimate variations within and across local populations.

Quantifying the potentially substantial benefits of active travel measures has been recognized early on as a promising approach to elevate the status of walking and cycling within the planning as well as the public health community (29–31). Cost-benefit analysis is a standard methodology in transport planning: in many countries, a road, bridge or cycle path will not be built unless the benefits can be shown to be greater than the costs. However, traditionally in many cases walking and cycling have not been included in economic valuation of transport projects (31–33), putting active forms of travel at a relative disadvantage since the full benefits are not considered. Thus, providing methodological approaches to include the benefits of active travel is one approach to moving walking and cycling up the transport policy agenda.

In response, in 2005 a multi-phase, open-ended project was established to develop the Health Economic Assessment Tool (HEAT) for walking and cycling as a harmonized method for economic valuation of health impacts of walking and cycling, based on best available evidence and international expert consensus (34, 35). Since then, implementation has been steered by a core project group, working in close collaboration with advisory groups, led by the WHO Regional Office for Europe and Headquarters.

The HEAT calculates: if x people cycle or walk y distance on most days, what is the economic value of resulting reductions in mortality? This calculation can serve different types of assessment, for example, of current (or past) levels of cycling or walking, such as showing the value of cycling or walking in a city or country; of changes over time, such as comparing before-and-after situations or scenario A vs. scenario B (such as with or without measures taken); and evaluating new or existing projects, including calculating benefit–cost ratios. The tool is intended to be robust but easy to use primarily by transport planners, traffic engineers, economists and special interest groups.

In 2007, an approach to calculating the economic value of reduced all-cause mortality from cycling (quantified using the Value of a Statistical Life VSL approach) was adopted at the first HEAT consensus meeting (34, 35). These international consensus meetings are a core part of the HEAT development to promote critical review, discussion and achievement of consensus on proposed options, including in cases where best expert judgement is needed (35). The HEAT process follows the following key principles:

- Robust and evidence-based
  Decisions are taken on the best available evidence with the view of providing a scientifically robust tool.
- Easily usable
  The HEAT is developed for the transport sector as the main target audience, thus for users who are likely to have limited

knowledge of epidemiology and public health. Simplicity in application is thus a key consideration for any decision taken.

- Transparent
  Decisions and any assumptions taken are made transparent.
- Conservative
  Methodological considerations are taken with an "at-least" approach.
- Adaptable
  While for as many as possible inputs, default values are provided to facilitate application, which in most cases can be adapted to reflect local conditions and approaches.
- Modular
  Users can select to run assessments for different modes of transport (i.e. walking, cycling and soon e-biking) as well as different impact pathways (physical activity, air pollution, fatal traffic crashes, and carbon emissions). In addition, HEAT is meant for integration into wider cost-benefit analysis as a modular component.

A key feature of the HEAT process is the involvement of experts from a range of fields that are relevant for the development and implementation of walking and cycling measures. To date, next to the coordinating team, more than 120 experts from epidemiology, public health, transport research and planning, health and transport economics, air pollution and environmental sciences, policy making, practice and advocacy from over 30 countries have contributed to the development of the HEAT across the different project phases.

Based on a systematic review of the literature (33), a basic approach designed for the European region was agreed to develop the first HEAT for cycling (36, 37), launched in 2009. An updated version of the HEAT for cycling and a new HEAT for walking were finalized at a second consensus meeting and launched in 2011 as a web-based tool (34) with a methods and user guide booklet. In 2013, the third consensus meeting discussed results from another systematic review (4) to update the methods for HEAT walking. A new HEAT version including an option to calculate health impacts from air pollution and road fatalities separately, and to take into account carbon effects of shifting to active modes was launched in 2017 (38, 39). In 2021, the first globally applicable version was presented (40). Future versions are expected to include e-biking and translations into different languages.

This paper discusses how the HEAT has been used over its more than 10 years of existence, and identifies lessons learned and challenges for the ways in which economic assessments of their health impacts can foster the recognition of walking and cycling in transport policy and practice.

2. Methods and materials

To collect information on the uptake of HEAT, a range of sources has been used:

- Applications saved in the HEAT online database by users between 2011 and 2015,
- Applications communicated to the HEAT coordinating team by email,
- Collections of applications gathered on behalf of the WHO Regional Office for Europe in 2012 and in 2021,
- Invitations to report applications to the HEAT mailing lists sent from the WHO Regional Office for Europe in 2015 (41),
- A systematic online search using the Google search machine and the PubMed literature database, carried out in summer 2015, and updated searches in 2017 and 2021 (42), using also Google Scholar,
- Responses to a questionnaire on the monitoring framework for the implementation of policies to promote health-enhancing physical activity in the EU and the WHO European Region (containing one question on HEAT) returned in April 2015 (43), and
- The reference lists of 3 systematic reviews on health impact assessments of active travel (22, 44, 45).

In addition, in 2015 an online survey with 8 questions on the experiences with using the HEAT was carried out (41). The survey focused on general use, applicability, and challenges around the HEAT, thus it is still of relevance even if tool functionalities have changed since then. Invitations were sent by email to 2,865 HEAT users known from the above-listed sources and other stakeholders, including the Transport, Health and Environment Pan-European Programme (THE PEP) (46) and the European network for the promotion of health-enhancing physical activity (HEPA Europe) (47). 263 responses were received (9% of the total sample) (41). Finally, 11 semi-structured interviews were carried out with selected HEAT users in 2015 to understand in more detail how HEAT had been used and possibly influenced transport policy and practice.

Web statistics on the HEAT use are available since its launch as an online tool in May 2011 through the Google Analytics tool (48); however, due to migration of HEAT to a new technical platform in 2017, long term trends are not fully comparable. The metric "non-bounce users" excludes users who had no interaction with the page (i.e., just opening, looking, closing), available as of November 2020.

3. Results

3.1. Overview of dissemination and uptake

Since the launch of the first online version in May 2011, the tool had over 544,000 page views by over 40,600 users. While originally developed for the WHO European Region, the HEAT use was widespread beyond Europe, with the top countries in the last 2 years (November 2020–2022) being the United Kingdom and the United States, followed by China, Germany, France, Italy, and Finland, Spain, Switzerland and Australia, in addition the to use of the tool by cities such as London, Shanghai, Helsinki, Vienna and Paris.

While HEAT was developed primarily for the transport sector, the majority of online survey respondents of 2015 came from the public health sector (43%), with similar shares of responses from transport (28%) and academic sectors (27%) (41). Twenty-two percent of survey respondents had not heard of or looked at the HEAT, 44% had at most entered some data to see how it worked. As main reasons for not using the HEAT, lack of time (41%) or lack of suitable data (38%) were quoted. About one third of respondents ($n = 78$, 31%) had done one or more full calculations (34). Of these, 47% estimated the value of future projected or hypothetical levels of cycling or walking, 22% the value of measured increases and 19% that of current levels of cycling or walking. Results were most often used for a presentation (39%), internal (37%) or published (27%) reports or an academic paper (15%). Main target audiences were a local authority or municipality (59%), a national authority/ministry (27%), a research body (23%) or a non-government organization (21%).

The data from the different information sources (see Methods and materials) yielded a total of 132 documented applications (41, 42), including 7 that mentioned HEAT but did not apply it in practice or were incomplete draft reports.

The remaining 125 applications included 52 technical reports and 38 academic publications, as shown in **Table 1**, as well as 12 government papers or guidance reports. Twelve of the publications qualified as government papers or guidance, i.e., documents issued by a part of an administration and/or guidance documents that promote the use of HEAT. There were also several reports from academic institutions or consultancies that were developed on behalf of administrative bodies, as well as research reports, in particular by local administrations.

Despite the wide-ranging searches and repeated invitations to report applications, in comparison to the web statistics, to date there is still only a limited number of documented uses of HEAT by government agencies, and a majority of those come from the United Kingdom. This may be due to an English language bias, as the HEAT has only been available in English (despite user guides having also been translated into German, French, Finnish, Polish, and Spanish), likely to reflect the differential uptake of the HEAT by certain countries. In addition, there is only limited evidence on the tool's direct impact on policy actions and decision-making.

While the HEAT has not been developed as a research tool, usage in almost 40 academic publications confirms its scientific robustness and usefulness in an academic setting, including for training purposes.

TABLE 1 Documented applications of the Health Economic Assessment Tools (HEAT), by type.

Type	Number	Percent	Examples
Reports	52	41.6%	
English	32	25.6%	(49–51)
Non-English	20	16.0%	(52–54)
Academic paper/abstract	38	30.4%	(55–57)
Government papers/guidance	12	9.6%	(58–60)
Other (case studies, slides, website etc.)	23	18.4%	(61, 62)
Total	125	100%	

In the 11 interviews carried out in 2015 with users (41), a number of strengths and weaknesses of the HEAT were identified (see **Table 2**).

3.2. Examples of applications

In this section we present selected examples of HEAT applications from academia, policy and practice.

3.2.1. Academia

3.2.1.1. An economic analysis of four Ciclovía programs

The Ciclovía is a regular multisectorial community-based program in which streets are temporarily closed for motorized transport, allowing exclusive access to individuals for recreational activities and physical activity. In this early application of the HEAT, a cost–benefit analysis of physical activity of the Ciclovía programs of Bogotá and Medellín in Colombia, Guadalajara in México, and San Francisco in the United States was carried out (55). The study found that the cost–benefit ratio for health benefit from physical activity was highly positive, ranging from 3.23–4.26 for Bogotá, 1.83 for Medellín, 1.02–1.23 for Guadalajara, and 2.32 for San Francisco.

3.2.1.2. Exploring the health and spatial equity implications of the New York city bike share system

In this study, the HEAT was part of the assessment scheme of the New York Citi Bike share system benefit at launch in 2013 and after expansion in 2015 (56). The study also discussed how further system expansion and utilization by residents in high-poverty communities could affect the potential benefit of the largest bicycle share system in the United States. The results showed that the greatest proportion of Citi Bike stations were located in low-poverty (i.e., wealthier) census tracts (41% per period), and there were no significant changes in station distribution during

TABLE 2 Strengths and weaknesses of the Health Economic Assessment Tools (HEAT) for walking or cycling.

Strengths	– Allows quantifying the magnitude of the health impacts compared to other (e.g., environmental) benefits. – Combination of health impacts and economic quantification. – Having a specific number gets people thinking and facilitates discussions and exchange with relevant bodies. – Evidence- and consensus-based approach, transparency. – Approach allows integration into existing transport appraisal systems. – Can facilitate the exchange between transport and health specialists, where a desire exists. – Tool now also adapted for global use. – Project coordination by the WHO adds to credibility.
Weaknesses	– In some audiences the use of Value of a Statistical Life and resulting numbers are not easily understood. – HEAT is not well known in local communities where many transport planning decisions take place. – Translations of the English tool and user guide into local languages are needed for uptake, in particular on the local level. – As long as it is not included in the official national guidance for transport appraisals, it will only be used seldom.

expansion. HEAT estimated an increase from two to three premature deaths prevented and an increased annual economic benefit from $18,800,000 to $28,300,000 associated with Citi Bike use. The findings underlined the potential for even greater benefits with advancing access in higher-poverty neighbourhoods and communities of colour.

3.2.2. Policy: Austrian Masterplan walking and cycling

The Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology has been involved in the development of HEAT since the very beginning and sponsored the first HEAT consensus meeting in Graz in May 2007. HEAT is currently promoted in three ways: they translated HEAT and the user guide into German when it was launched as an online tool in 2009 and they make HEAT available on the ministries' website (61). They also calculated the societal economic value of health effects from current and levels and aspired policy goals for cycling in Austria using the HEAT in 2009 and again in 2014 (62); and they included a mention of the HEAT into the National Masterplan for Cycling (p. 43) (58). The HEAT results have also been used regularly in presentation and communications of the ministry, e.g., in relation to a cycling tour of the former Minister of Environment.

3.2.3. Practice: health impact assessment of fare increases and service cuts on public transport (Boston, Massachusetts, Uniteed States)

The Metropolitan Area Planning Council used the HEAT as part of a rapid health impact assessment to calculate the economic costs of potential increases in mortality as a consequence of decreases in regular walking due to two proposals to increase fares and cut services on public transport (63). Results showed that across the two proposals there would be 9–14 additional deaths per year due to decreased physical activity, which could be valued at between $74.9 and $116.5 million per year. This significant cost associated with the proposed fare and service changes was second only to the cost of time lost to congestion. The resulting costs would have by far exceeded the budget shortfall that the proposed changes sought to address. According to the authors, the results contributed to lower fare increases and fewer service cuts than initially proposed.

4. Discussion

With the growing popularity of walking and cycling as healthy and sustainable travel modes, over the past decade, economic assessments of health impacts from walking and cycling have become more established, thanks to practical yet robust tools such as the HEAT or the Integrated Transport and Health Impact Modelling Tool (ITHIM) (64). The large number of officially published applications by academia, governments, NGOs and consultancies demonstrates a wide recognition of the HEAT as an established and valued tool to calculate health and carbon impacts from active transport interventions. It was also found to be the most widely used health-impact assessment tool for active travel by two systematic literature reviews (44, 45). Important milestones of this progress have been the endorsement of the HEAT in the Global Action Plan for Physical Activity (p. 69) (16), and most recently in the Pan-European Cycling Masterplan (17).

4.1. Success factors and achievements of HEAT

HEAT has been well-received and often characterized as an "eye-opening" tool by a broad audience of transport and health advocates, both within and outside of governmental institutions. This is due to monetization of health benefits using the value of statistical life approach results in benefit estimates which exceed general expectations. In some occasions, this plain quantification of impacts in monetary terms has earned active travel modes "a seat at the table" (41), resulting in more equal consideration of walking and cycling in decision-making processes. While examples of a direct impact on policy decisions remain rare, HEAT results have equally resonated in places with low levels of walking or cycling to make a basic case for their benefits, as well as in places with well-established walking or cycling cultures to make more nuanced benefit-vs.-cost arguments. This is particularly the case in countries where economic appraisal is an established practice, such as the United Kingdom: here, the HEAT has become very established because there is a strong tradition of putting transport proposals through an economic analysis (41, 59). HEAT also has proven helpful to put benefits from physical activity in perspective to harms from air pollution and insufficient traffic safety while walking or cycling. While research has shown that in general benefits of active travel outweigh the risks (22, 65, 66), HEAT provides users with the possibility to verify or challenge this assumption for their particular local case for example by comparing impacts in a more and a less cycling friendly city (67), helping to counteract unbased fears or to substantiating calls for safety improvements (68). The recognition of the potential role for active travel in efforts to reduce urban carbon emissions (19) further increases the usefulness of the HEAT, supporting the inclusion of this argument into appraisals of different policy options.

Being steered by the WHO and making co-creation with leading experts from around the world part of its key approach, the HEAT has earned a status of credibility and scientific robustness by academics, advocates and governments alike. Two national agencies, namely in England and Austria, have officially endorsed the HEAT at some point (41).

Arguably the HEAT tool's greatest success factor is to present the impact assessment as a short sequence of steps, when in fact the calculation needs to rely on a fairly complex set of data, methods and assumptions (36, 38, 40). Throughout its evolution, the HEAT has made it a top priority to require minimally inputs to address user needs, while providing as much of the required data and calculations as possible in the background. In the simplest cases, a handful of inputs is sufficient to obtain results.

At the same time, over the years the tool has evolved to accommodate both a more diverse set of applications as well as increasingly diverse audiences and levels of expertise.

4.2. Limitations and challenges of HEAT

Despite its considerable success, substantial challenges remain for HEAT, many of which apply to HIA tools for active transport in general. The most common difficulty reported by HEAT users is how to obtain data on active travel use. By design, HEAT leaves the burden of assessing or estimating levels of walking and cycling to its users. While in some circumstances hypothetical calculations based on (often crude) scenario assumptions are sufficient, many users desire to quantify concrete impacts of existing or planned programs or infrastructure projects. However, in particular for small scale projects assessing walking and cycling levels accurately and predicting effects of interventions on future active travel use remains a challenge. Although data collection is outside the immediate scope of HEAT, there is a role for the HEAT project to guide users through the ever-evolving methods for active travel estimation, as the institutional burden to use online surveys or app-based tracking becomes smaller over time.

A limitation of HEAT is that health impacts are assessed based on mortality risk (i.e., premature deaths and road fatalities) only. Although there is ample evidence aor impacts of active travel on morbidities (5–9), the methodological implications of including these in tools such as HEAT have to date presented to be at odds with its main goal of providing a simple-to-use tool. Thus, health impact estimates derived by HEAT present relatively crude ballpark estimates and do not allow specific conclusions regarding health outcomes such as mental health or cardiovascular disease.

HEAT uses the VSL to quantify the societal value of reductions in mortality risk. The values are widely available (69), and recently a methodology was integrated into the HEAT tool to estimate VSL estimates for each country worldwide (38, 40). While widely used in transport appraisals and elsewhere, monetization based on this approach does not provide estimates in terms of health care savings or other governmental expenditures, and as such remains hard to explain, particularly non-transport experts and some local decision-makers.

4.3. Outlook

The primary goal of HEAT and other HIA tools for active travel modes is to provide decision-making processes that affect walking and cycling with robust, quantitative inputs. This goal has been pursued through a three-pronged strategy: (a) provide a scientifically robust tool broadly accepted by experts and governmental institutions, (b) provide a simple-to-use tool easily picked up by practitioners within and outside of governmental institutions, and (c) disseminate the tool and related success stories as widely as possible. While tool development remains ongoing (e.g., integration. Of e-biking), with the launch of the globally applicable version the priority now will shift towards wider dissemination.

As with many innovations, successful adoption of the HEAT has been greatly helped by enthusiastic “early adopters” who see its potential and make the effort to try it out and then advocate for it. More strategically developing and supporting networks of such advocates will be a key task for building capacity and increasing the use of the tool in the future. The challenge is identifying the right people, getting them to spend time to apply it to a specific scenario or case study and to promote it at a national and/or local level.

Continued strategic communication, capacity building and dissemination is thus another key task for the future, along with translation of the tool, user guide and the website, particularly into languages making it amenable outside of Europe, e.g., into Portuguese or Spanish. Another element is to collate more case studies that are applicable to low- and middle-income contexts supporting a more global uptake of the HEAT, particularly considering the recent adaptation of the tool for global use.

Finally, lack of systematically collected data on walking and cycling was identified as a key barrier to use of HIA tools such as the HEAT. Users stated that trying the HEAT often had an unexpected outcome of helping them realise the gaps in their data. Supporting international, national and sub-national transport authorities in collecting better data on walking and cycling should be another key component of a future HEAT dissemination strategy.

In conclusion, the contribution of walking and cycling to addressing public health, sustainable transport and climate goals are substantial, particularly in settings facing increasing levels of urbanisation and motorisation. Therefore, integrating health impacts into transport economic assessments should be a standard approach for all transport planning approaches to ensure that the most cost-effective and thus sustainable investments are made.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

SK: conceived and designed the manuscript and wrote the first draft. SK and NC: wrote sections of the manuscript. All authors contributed to the article and approved the submitted version.

Funding

The HEAT user survey was co-funded under a LIFE + grant to the European Cyclists' Federation from DG Environment, European Commission.

Acknowledgments

We gratefully acknowledge the support received by Sophia Röckel, Pia Andersen and Christian Schweizer, Division of Communicable Diseases, Health Security and Environment, WHO Regional Office for Europe, in carrying out the HEAT user survey and collating information on use of the HEAT. We also thankfully acknowledge the project lead by Randy Rzewnicki, formerly European Cyclists' Federation, in the 2015 HEAT user survey. We further thank Kitty Greenwood, Yingjie Huang (Charlotte), Talia Shehadeh and Oscar Schilly, kindly supervised by Audrey de Nazelle, Faculty of Natural Sciences, Centre for Environmental Policy, Imperial College London, for their review of the HEAT tool and identification of case studies. The authors also gratefully acknowledge the inputs of the experts involved in the development phases of the HEAT and the consensus meetings. The full list of experts can be found at www.heatwalkingcycling.org/#acknowl.

Conflict of interest

The authors affiliated with the World Health Organization (WHO) are alone responsible for the views expressed in this publication and they do not necessarily represent the decisions or policies of the WHO.

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frontiers | Frontiers in Sports and Active Living

TYPE Original Research
PUBLISHED 12 June 2023
DOI 10.3389/fspor.2023.1127592

OPEN ACCESS

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RECEIVED 19 December 2022
ACCEPTED 25 May 2023
PUBLISHED 12 June 2023

CITATION
Corr C, Murphy N and Lambe B (2023) Beyond the big city: using a systems approach to cultivate a cycling culture in small cities and towns in Ireland.
Front. Sports Act. Living 5:1127592.
doi: 10.3389/fspor.2023.1127592

Beyond the big city: using a systems approach to cultivate a cycling culture in small cities and towns in Ireland

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Urban mobility and how people move in our towns and cities is garnering more attention, as solutions are sought to multiple challenges faced by residents; health and physical inactivity, climate change, air quality, urbanisation and accessibility. Traditional, siloed approaches limit impact and collaborative, systems approaches hold promise. However, systems approaches often remain theoretical and few practical applications of their added value have been demonstrated. This study illustrates how a systems approach can be used to underpin the development of a 9-step process to generate solutions for action on active mobility. The development of a systems map and a theory of change framework are key outputs of this 9-step process. The purpose of this paper is to describe how a systems map was developed in an Irish town utilising broad stakeholder engagement to map the variables that influence cycling in the town and to identify the leverage points for transformational interventions.

KEYWORDS

systems approach, cycling, active travel, participatory planning, collaborations and partnerships

1. Introduction

Ireland is a car dependent society with one of the lowest levels of active transport and the second highest level of car dependency among EU citizens (1, 2). The national prevalence of active transport has decreased dramatically since the 1986 census when active travel accounted for over 32% of all journeys. Irish census data has indicated that active transport to work and education (primary, secondary and tertiary) has decreased further to a state average of 16.6% in 2016, with public transport use also falling in this time period. Household car ownership has increased its upward trend and in 2016, 81.9% of households across that state owned a car. The National Travel Survey (3),, found that journeys by car accounted for 73.7% of all journeys, rising to over 8 in 10 journeys in thinly populated areas. The most recent Eurobarometer poll (2022), showed Ireland was only one of five EU member states where car dependency levels has increased in the last three years.

In 2021, in Ireland, the transport sector was responsible for 17.7% of Ireland's greenhouse gas emissions, and road transport accounted for 94% of all transport emissions (4). Between 1990 and 2021, transport was responsible for the greatest overall increase in Ireland's greenhouse gas emissions. Transport carbon emissions have become the second largest source of CO_2 emissions by sector (5). Despite an unprecedented decline in road transport activity as a consequence of COVID 19 lockdown measures in 2020, transport emissions rebounded in 2021, growing by 8%. Global CO_2 emissions from road transport returned to just 3.6% below the 2019 level in 2021 to 5.86GT of CO_2 (5). Globally, many cities and urban areas face similar challenges and have unintentionally become car-centric by design, with continued accommodation of car growth through building of additional roads and parking capacity, thereby fostering car use.

Increasingly, cycling is seen as a key part of future transport systems. The global pandemic of COVID 19, the war on Ukraine and subsequent turmoil and uncertainty in energy markets, has increased the urgency of countries managing energy demand through the implementation of behavioural changes related to mobility (6). Both of these phenomena have given rise to new, compelling motivators for cycling. Social distancing and hygiene concerns led initially to a move away from public and shared transports (7, 8). Cycling allowed for avoidance of close contacts and became a valuable alternative to maintain or increase transport capacity (7). These motivators coupled with high fuel costs and uncertain energy supplies have helped to overcome some of the resistance to the reallocation of space for cycling facilities and have enabled rapid deployment of cycling infrastructure in some cities across the world (7).

The co-benefits of a modal shift to cycling are compelling. These include improved air quality, reduced noise emissions, reduced congestion, alternative uses of public space, more equitable mobility options (9) and the well documented health benefits (10, 11). There is an ever growing body of evidence of the impact of cycling on anxiety, stress and vitality (12, 13). As discussed by Patz et al. (14), focusing on the solution to climate change through a health lens may accelerate the shift to a low carbon society and address the greatest health challenge facing developed countries of rising non-communicable disease and decreasing physical activity levels.

The roll out of cycling infrastructure in smaller cities and towns has not been implemented on a similar scale per population to that seen in larger cities worldwide, with the exception of France, where a country wide response saw cycling measures implemented in 207 urban areas (15). The design of smaller urban areas has created a dependency on the private car as the main source of transport, leading to resistance to the reallocation of space necessary for the provision of cycling infrastructure. Smaller cities and towns have fewer resources and smaller teams which can provide greater challenges for implementing sustainable mobility policies. Nonetheless, smaller cities and towns often have well-connected social communities and more walkable and bikeable journeys (16). For smaller cities and towns, cycling presents opportunities to fill the gap in weaker public transport systems, offering park and ride and first and last mile solutions when combined with public transport. The growth in use of E-bikes has also demonstrated the potential to replace longer and more arduous journeys (17). It has the potential to be a public transport offering in its own right and a tourism offering for smaller cities (18).

This action research addressed the challenges faced by smaller cities and towns to reducing car dependency and creating a modal shift to cycling through a systems approach. According to Rutter (19) "systems thinking provides a framework to help examine the factors involved in a problem, the relations between these factors and changes over time". It has been widely applied to problems arising in complex social, ecological and more recently public health systems. Whilst considering the approach, numerous theories and models, rooted in transport and health and previously applied to examine active travel behaviour were reviewed (20–23). The Physical Activity through Sustainable Transport Approaches (PASTA) consortium reviewed 26 published frameworks and combined behavioural concepts, structural features and a large number of determinants in a single framework. The study concluded that large research projects may still merit a study specific framework (24). Similarly, studies involving policy development have called for study specific frameworks to allow for adaptation to local contexts, the local socio-ecological system, innovation and learning (25). Hence, this action research adopted a systems approach with broad stakeholder engagement to encourage vision-orientated and community-based decision making towards a framework specific to the context.

A systems approach allows for dialogue between stakeholders, enabling them to learn how to change their patterns of decision making and emphasise project-based experimentation and social learning (26). Furthermore, the involvement of stakeholders results in better knowledge, better decisions, capacity building, enhanced social capital and therefore better success (27). The process of enabling idea formation, solution generation and learning, contributes to the sense of ownership and the building of a local platform necessary for implementation. Taken originally from the field of systems science or systems dynamics, this approach has many methods of application and terms are often used interchangeably. The development of a systems map is one common method associated with systems science. The process of drawing the map is as important as the map itself, as stakeholders communicate and collaborate to identify different elements of the system and their interconnections. This broad cross sector coordination can lead to large scale impacts in systems (28). Kohl et al. (29) recommends a systems approach focusing on populations, rather than individuals to increase physical activity worldwide. More recently, an OECD report on Redesigning Ireland's Transport for Net Zero (30), stated that "patterns of behaviour, including mobility, are the product of the systems they are embedded in. Transport systems have been shaped by existing policies but similarly, a shift in policy has the potential to redesign systems and enable large-scale behavioural change." Similarly, the Intergovernmental Panel on Climate Change (IPCC) seeks transformative change to reverse current patterns of behaviour, "system-wide change that requires more than technological change through consideration of social and economic factors that, with technology, can bring about rapid change at scale" (31).

Following these recommendations, this research developed a pragmatic 9-step process, underpinned by systems science, to develop a cycling culture in Kilkenny city, Ireland. Specifically, the purpose of this paper is to describe the first five steps in the process. This involved multiple methods of stakeholder engagement to develop a systems map of the variables that influence cycling in smaller cities and towns and to identify the leverage points for transformational interventions.

1.1. Study area and context

Kilkenny county (population 103,685) is located in the south east of Ireland and it's main urban centre is Kilkenny city with a population of 26,512 (32). It is the 4th largest urban area in the Southern Region of Ireland and has experienced a population growth of 8.6% over the 5 year intercensal period since 2011. The National Planning Framework 2040 envisages a 30% population growth in Kilkenny up to the period of 2040. The population of the county living in urban areas is increasing, from 35.3% in 2006 to 37% in 2011 and to 40% in 2016. However, Kilkenny is still a predominantly rural county in terms of population. The city is the 8th largest employment centre in the state, and is a self-sustaining regional driver, with a daytime working population of 13,738. Kilkenny has excellent road links to Waterford and Dublin. The existing rail links to these cities have limited schedules for commuters, with no service for the morning commuter on the Waterford route. The National Transport Authority introduced a Kilkenny City Bus service late in 2019, with two routes, which has grown to over 5,000 passenger journeys weekly. The city is also served by private bus providers and a demand response service, the Local Link. The projected population growth has the potential to result in a significant increase in the demand for travel in the city with the current modal share (**Table 1**) (32).

Kilkenny city is predominantly flat and compact with moderate levels of traffic congestion and a population density of 2,115.9 per km^2. It is approximately 3 km wide and 4.5 km long with many destinations easily accessible by foot or by bike. The County Development Plan (33) has set out ambitious targets for modal share in Kilkenny city, achievable through the implementation of compact growth and the 10 min city concept. Despite ambitious aims and objectives, Kilkenny city has struggled to reduce car dependency. A mobility management plan was adopted in 2009 and an inter-agency Smarter Travel committee was established. Although some major infrastructural projects were delivered, including two additional river crossings, there was no evidence of increased modal share of active modes (34, 35). In Kilkenny city, over 65% of males use motorised transport and 64.54% of females use the car as their means of transport for journeys to work or school. The percentage of those using cycling as a means of travel in Kilkenny fell from 13.65% in 1996 to 3.12% in 2016 with the greatest decline in secondary school students (13 to 18 years) from over 40% in 1996 to just over 3% (3.24) in 2016. Compared to the national average of 4.43% in 1996, Kilkenny had a high percentage of people cycling as a means of transport at 13.65%. In 2016, cycling as a means of travel in Kilkenny was just above the national average of 2.68%.The allocation of 20% of the transport budget to active modes in 2020 and the installation of active travel teams in the local authorities presents new opportunities to drive transformational change. The researcher is embedded in the local authority, alongside an Active Travel team of three staff. The reach of this team is extended through an inter-departmental steering group and a broad stakeholder group, focusing on sustainable transport in the city.

TABLE 1 Modal share targets taken from the kilkenny city and county Development plan (33).

	Walk	Cycle	Public transport	Car
2016 Census	23.3%	3.1%	4.0%	63%
2040 Target	35%	10%	15%	40%

1.2. Methodology

1.2.1. Research design

The research consisted of creating a systematic 9-step process designed to develop two key outputs; a systems map and a theory of change framework, based on Nutbeam and Bauman's evaluation framework (36). These steps, related activities and how they are aligned are illustrated in **Figure 1** below. Step 1, the formative research, was conducted encompassing a review of the literature, policy context and planning framework and an analysis of mobility data and trends. This step allowed the researcher to build on existing research and gain an understanding of the local context, mobility patterns and trends. The detailed step 1 findings are beyond the scope of this paper and are presented in full on the project website (37). This paper describes the development of the first key output, the systems map (steps 2–5). Steps six to nine, relate to the second key output, the theory of change framework, where the systems map is translated into a pragmatic format easily used by stakeholders and familiar to practitioners. Due to the depth of the engagement and length of the process, this will be published separately. This research was approved by the research ethics committee of Waterford Institute of Technology (WIT2021REC014).

2. Methods

This section describes the methods, and where appropriate, the data analysis, for steps one to five.

2.1. Step 1: formative research

A literature review was conducted to identify the factors that influence cycling in cities and towns. A google scholar alert was set up using the following keywords; utility cycling, cycling for transport and active travel. Frameworks, determinants and factors influencing cycling were reviewed from 2016 onwards. The European, national and local policy and planning frameworks were reviewed and objectives relating to transport planning and active travel were documented.

Mobility trends in the European, Irish and local context were identified through extraction of data from the following sources; the Eurobarometer (1, 2), the National Travel survey, the Irish Sports Monitor dataset (38) and the Census of Ireland (32). Modal share of all means of travel was calculated and comparisons were made by towns of similar size, gender and age groups between 1986 and 2016.

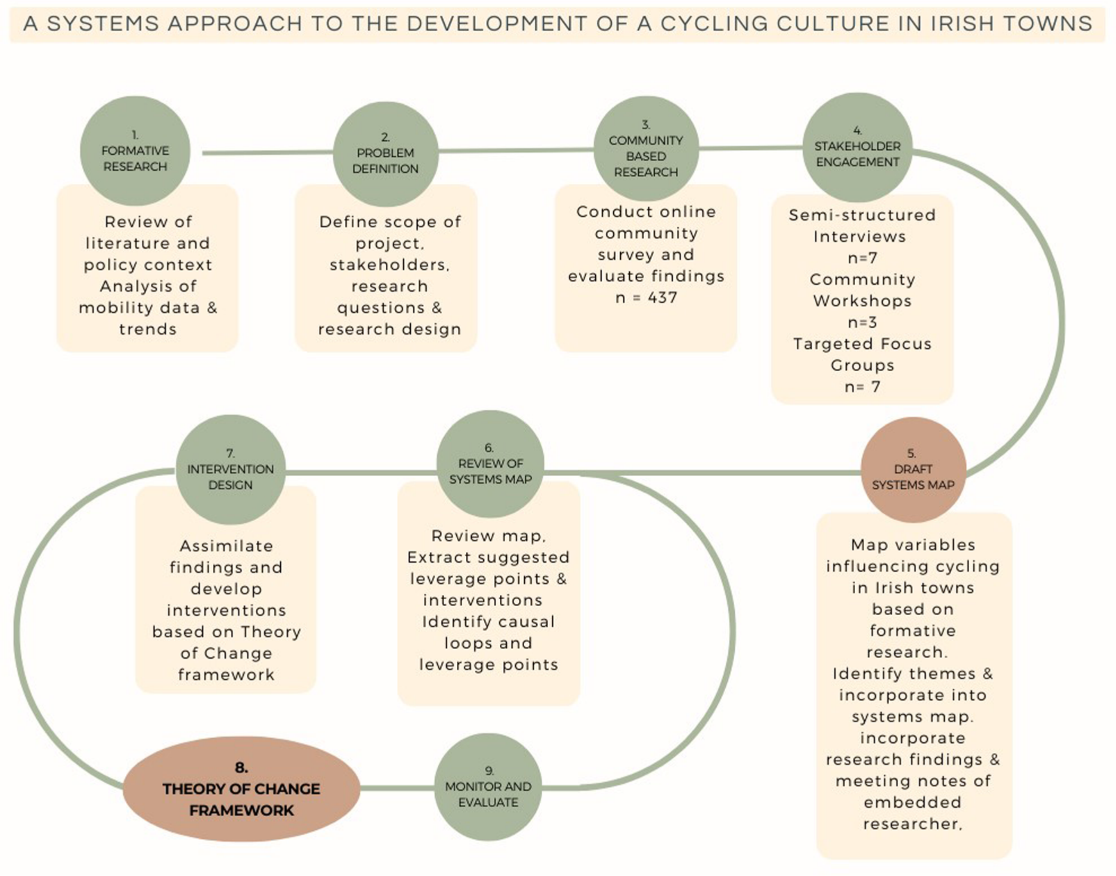

FIGURE 1
The 9-step process used for developing a systems map and theory of change framework.

2.2. Step 2: problem definition

Research team meetings and meetings with the research partners and other stakeholders allowed for deliberation and definition of the research objectives. Initial discussions were through the Cycle Kilkenny stakeholder group, established by the Local Development Company to explore Cycling in the City. As the process evolved, the discussions were shaped by the development of the Local Transport Plan, incorporating active travel objectives, led by the local authority. The functional area of the research was defined, the stakeholders involved were identified and the research objectives were identified.

2.3. Step 3: community based research

The community wide survey was conducted to determine the needs of the community for mobility in the city, liveable streets and public spaces and to identify the barriers and enablers of cycling. The survey contributed to step one and two, the formative research and the problem definition. Furthermore, the survey gathered evidence on public attitudes to develop the narrative on how and why cycle planning will meet a range of public interest and stakeholder objectives. Lastly, the survey created awareness in the community of the project's goal, to cultivate a culture of cycling within the community, and thereby gained community support and involvement and enhanced the collaborative process.

The community wide survey was conducted in June and July 2019. Ireland was re-opening following a full lockdown and moving into Phase 2 of Covid-19 restrictions; people were now allowed to travel within their county and meet up to six people from outside their household. Organised indoor events were not permitted and working from home was to continue where possible. For these reasons, the survey was hosted on the Survey Monkey platform, a non-probability (convenience) sample was generated ($n = 437$). The sampling method was unrestricted and self-selected (39). The survey was piloted ($n = 30$), final edits were made and the survey was circulated through social media platforms of the organisations represented in the original Smarter Travel committee.

Specifically, the survey consisted of 35 questions categorised into six distinct sections. The first section contained questions on participant demographics taken from the Irish census (2016). Additional items such as physical activity (40), bike and car ownership and residential location were also included. Community accessibility was measured using the Perceptions of the Environment in the Neighbourhood Scale (41, 42). Two questions were amended to be more cycling specific and reflect more recent findings suggesting the importance of segregation (43) and network connectivity (44–46). The community attitudes to cycling section was a seven item measure, based on the theory of planned behaviour with the additional items to capture habits and perceived social norms (42, 47). Community needs were assessed with questions adapted from The Town Centre Living Initiative (48) and a Town Centre Assessment carried out under the Intereg programme by South Ayrshire Council (49). The section on barriers and enablers consisted of variables that have been widely reported in the literature and in recent national surveys conducted in two low cycling countries; Scotland and New Zealand (3, 50). Cost of parking at work and trip chain information variables have been included based on previous research in Kilkenny (51). Lastly a question on the propensity for modal shift was adapted from the Switch Tool Kit (52).

2.4. Step 4: stakeholder engagement

The stakeholder engagement was designed to elicit a greater understanding of the complex issues and the nuances that shape cycling patterns in a local context. Critically, a rich collection of experiences was gathered and diverse stakeholders were engaged early in the participatory planning of interventions. An in-depth qualitative study was conducted using several methods of data collection to ensure a broad and diverse engagement and to capture the voices that are often unheard. These methods included semi-structured interviews with key stakeholders, community workshops, targeted focus groups and reflective note taking following meetings and events throughout the engagement process. This approach enabled the researcher to understand the challenges faced by key stakeholders working at the intersection of transport and health. Throughout the process, stakeholders were encouraged to share potential solutions to mobility challenges, to identify possible leverage points and suggest interventions.

For participation in the stakeholder engagement, respondents were contacted in advance, by email or phone, and invited to participate. Upon confirmation of attendance, follow up emails were sent to obtain informed consent and permission for recording, to describe the purpose of the study and present the interview or topic guide schedule. Interviews were recorded using a dictaphone or through the zoom platform. All interviews and workshops were transcribed verbatim, de-identified and imported into NVivo (released in March, 2020). Researcher notes and memos were also imported into NVivo.

2.4.1. Semi-structured interviews

Semi-structured, face-to-face interviews were conducted with key stakeholders in May and June of 2020. The set of stakeholders represented those in key decision maker roles at national and regional level, cycling advocates and city centre traders ($n = 7$). An interview guide was developed based on the researcher's knowledge of the factors influencing cycling and the local context. The interview guide prompted respondents to describe their ideal city and possible mobility solutions, to discuss challenges to mobility and the necessary steps to help overcome these challenges. Interviewees were encouraged to share their unique personal and professional experiences of mobility and cycling in the city.

2.4.2. Community workshops

Community workshops were conducted through three channels, the Public Participation Network (PPN); a forum for citizens involvement in decision making, the Chamber of Commerce, and Cycle Kilkenny; a group of organisations, including the local authority, working together to promote cycling in Kilkenny. The workshops moved to an online format on the zoom platform due to COVID-19 restrictions. Invitations were extended and permissions were sought through the three organisations. The workshops all followed a similar format. Firstly, information was presented on the demographic and travel trends, mode shares and the local policy context. Depending on the number of attendees, questions were then posed to all attendees or smaller groups with facilitators, with targeted probing of issues specific to the experiences and expertise of the participants. Issues arising varied greatly with the diverse stakeholders. Existing cyclists focused on the difficulties experienced moving through the city, cycling infrastructure deficiencies and the ideal cycling city. Non-cyclists discussed the barriers they faced to cycling, the forced car-dependency, the lack of alternative mobility choices and possible solutions. Participants were invited to use the chat function throughout the workshops. The smaller workshops were recorded and transcribed. Note-taking was used with break-out rooms and additional facilitators for the larger workshops.

2.4.3. Targeted focus groups

The online nature of the survey led to under representation of certain cohorts of the population. These were identified through a comparison of the respondent's data with the population demographics from the census. Typically, those missing or under-represented were the cohorts of the population that encounter limitations in how they engage with and move through the cityscape and those who traditionally face barriers to engagement. A targeted series of seven focus groups were conducted with the following participants: people with chronic health issues, people with an intellectual disability, people with physical disabilities, older adults, single parent families, members of the travelling community and members of migrant communities. The workshops and conversations focused on needs and experiences in regards to mobility, accessibility and public space. These workshops were conducted in partnership with the enterprise partner and analysed separately. The findings captured the experience of individuals and together the individual perspectives created a holistic picture and understanding of how people move through and interact with their city (53).

2.4.4. Reflective note taking

The stakeholder engagement process was enriched by the embedment of the researcher alongside the newly formed active travel team. This enabled the researcher's involvement in, and attendance at planning and project meetings with city traders, elected representatives, strategic policy committees and transport authorities. A Sustainable Transport group was formed for this process with representatives from the local authorities, planning, transport and environment, and other stakeholders. Following three meetings, an application was made to Interreg Europe for a peer review process. This resulted in a two-day workshop with in-depth discussion with five experts in sustainable transport focusing on the mobility needs in Kilkenny. The Interreg Europe team facilitated the workshop with the peers, the local authority and other key stakeholders. Following this, a decision was made to extend the Sustainable Transport Group to a wider group of stakeholders and the local authority began the process of developing a Sustainable Urban Mobility Plan. Insights and understandings were gained throughout this process by the researcher. Further learnings were gained through attendance at a study visit with the Dutch Cycling Embassy undertaken by the Active Travel team and political representatives, meetings with the National Transport Authority and team meetings with the Active Travel team. Regular meetings and bike rides took place with cycling advocates. Over 50 workshops and meetings took place in the engagement process. Reflective notes were recorded during and after meetings and added to NVivo as memos. Prompts for note taking included discussions on challenges faced by the stakeholders, problem definition, and novel and innovative solutions.

2.4.4.1. Stakeholder engagement data analysis

Several data analysis strategies were considered. The envisioned outcome required identifying, analysing and reporting themes to build the systems map which led the researcher to choose thematic analysis. This approach does not begin with a theory or hypothesis to be tested but instead adopts an inductive approach to data analysis (54). Responses were not grouped in predefined categories but rather salient categories were derived from the data itself. Categories emerged through several rounds of coding. Following transcription, documentation of meeting notes and familiarisation with the data (round 1), three additional rounds of coding were applied to the data. This analysis was applied systematically to all qualitative data. The rigor of the process was enhanced by the use of NVivo software analysis for organising and documenting the data analysis process. This platform allowed for the synthesis of the findings of all the qualitative engagement methods. The method used was based on the step-by-step approach of conducting a thematic analysis presented in a study exploring rigor and trustworthiness of qualitative research (55). This method offers a systematic approach that increases the traceability and verification of analysis. Reflective thoughts were captured throughout in memos. In round two, initial codes were generated by two researchers, coding was compared and a coding framework was developed. In round 3, the relevant coded data was sorted and collated. Round 4 reviewed the coded data to identify themes. Themes were collapsed or separated as needed. Themes and subthemes were vetted by team members. Themes were defined and named and the scope and content of each was described. The final themes with supporting quotes are presented in **Table 2** and were incorporated into the systems map.

2.5. Step 5: draft systems map

A systems map was drafted by the researcher based on the findings of the literature review using the KUMU online platform. The initial draft of the systems map was adapted from the Global Action Plan on Physical Activity 2018–2030 (GAPPA). The GAPPA map sets out four strategic objectives; Create Active Societies, Create Active Systems, Create Active People, Create Active Environments. The factors identified from the literature as influencing cycling were added to the maps as elements. The first draft of the map was prepared prior to the stakeholder engagement and was presented to prompt discussion at the community workshops and meetings of the Sustainable Transport Group. The majority of issues arising throughout the community engagement process reflected the findings of the literature. However, following the thematic analysis of the qualitative research, the map was restructured and a fifth strategic objective; Create Safe Environments, was added. Leverage points, places within a complex system where a small shift in one thing can produce big changes in everything (Meadows, 1972), were suggested throughout the engagement and recorded. Building the map was an iterative process, throughout the research, as the researcher worked alongside the Active Travel team and incorporated the learnings from planning and project meetings. The map is presented below in **Figure 2**.

3. Results

This section presents the results of Steps 3, 4 and 5.

3.1. Step 1

Findings of the literature review informed the research design and initial draft of the systems map. Mobility trends were summarised and the detailed analysis is presented on the project website together with a review of the policy and planning context (37).

3.2. Step 2

Through research team meetings and meetings with the research partners and other stakeholders, the following research objectives were formulated:

- Adopt a systems approach to map the variables that influence cycling in Kilkenny City

TABLE 2 Themes and sub themes with supporting quotes from all stakeholder engagement data collection methods.

Theme (with supporting quotes)	Sub Theme
Time of change and transformation, build capacity to adapt, new skills sets	
"I think Kilkenny has a really great opportunity for a regional town to turn the narrative around, that's a narrative that's embedded in a lot of wider challenges around the future of our town centres."	Changing social norms for mobility
	Building safe, segregated cycle ways as a catalyst for change
	Overcoming reluctance to discommode vehicular traffic
"The single greatest challenge is fear, I think people have a fear of change, what we're looking at is a major cultural shift, it's not tweaking around the edges anymore, what has to happen for a place like Kilkenny has to be quite radical but it has to be done in a way that's participative and that people are brought on board."	Overcoming resistance to change
	Responding to the needs of cyclists
	Retrofitting and reallocating space
"The drive is there to do it so I think if the willingness is there to do it amongst all actors, there's a great opportunity"	Seizing opportunities in a time of change
Working structures and statutory processes, evidence based and impartial decision making	
"I don't doubt the challenges that's ahead in trying to bring the focus back on to the smaller towns. That's effectively what we are. For all our lofty ideas about the city and all that, we are still a small regional town and I think we need to continue to look across at potential partners in other European municipalities"	Addressing a skills deficit
	Building capacity to deliver change
	Desiring and striving for high standards
	Developing relationships with funders
"we had city engineers who wanted to make progress on it, we had planners in the planning section who wanted to make progress on cycle infrastructure. I'm not sure if we had the necessary skill set in the Local Authority to see that from a hard road engineering perspective to a cyclists perspective and again there lies the challenge"	Needing political will
	Negotiating local and national policy
	Negotiating planning and political processes
"I think there needs to be a whole of government approach on something like this. The Dept of Education will not see it as their problem or spend anymore money to buy a bigger site that would allow good parking for the bikes or rooms for lockers – but they just don't see it. There needs to be a shift in their thinking"	
Collaborations, cross sectoral work, multi-disciplinary teams	
"You can't impose systems on people or on business who are going to be struggling even more now, that they don't want, so I think it's really important that we do that and we take on board the views of everyone who has a stake hold in the town"	Needing a multi-stakeholder approach
	Cycling as a cross-department function
	Thinking beyond cycle lanes ancillary cycling supports
"It's nobody roles, Sports Partnerships do a bit, An Taisce do a bit, the independent cycle training providers do a bit it. It falls under everybody and it falls under nobody specifically"	Understanding others roles and perceptions
	Overcoming lack of continuity in roles
Community Engagement, local knowledge, place based solutions	
"it's about the likes of a champion in certain schools and we pretty soon identified that there were schools that the principal or some of the teachers were cyclist themselves. Cyclists in the terms of recreation or commuter cyclists and then they just get the whole idea and they want more of it"	Cycling initiatives aimed at targeted groups
	Developing localised solutions
	Engaging the wider community
	Modelling behaviours and champions
"Cycle to work…the target market there should be the 10% that are living within 5 or 6 km of the work and it's not the 500 people in the workplace, it's the 20 or 30 that we should capture that can easily transfer, that don't have chain journeys."	Partnering with schools and workplaces
	Understanding others roles and perceptions
Future proofing, forward planning, monitoring and evaluation	
"We are the right size and they have designed Kilkenny well with the neighbourhoods and 10-minute city piece"	Needing a cycle network and central cycle access route
"Biggest challenge to me is the fact that we are a medieval city and it is mission impossible to provide space for everything and the solution is the notion of making the Nore the link, that you connect to the Riverside walk from wherever you are and then you're off road and you can cycle to wherever."	Needing and recognising the importance of participatory planning
	Optimising land use to reduce transport demand
	Providing alternatives to overcome car dependency
	Using demand measures to overcome car dependency
	Utilising research and data
Planetary and human health, healthy communities and town centres	
"if you create wow, well, you've made a friend, you're already winning. So if you do the same with your town, you're winning with tourists and if you can make your residents say wow? That's when they take pride and all sorts of things"	Accommodating and encouraging city centre living
	Being a compact and sustainable city
	Preserving and or developing vibrancy of urban centres, Regenerating spaces, Creating the wow factor
"we have to reimagine what our towns look like and what the spaces are for and that includes the periphery, includes the estates on the edge of the town and how that all interconnects"	Generating connectivity, connecting destinations and recognising the needs of the rural dweller
"It's a real aperitif before work and a refresher after work, 10-minutes of fresh air and leave work behind and look forward to what you are going to do for the evening."	Connecting with nature and accessing green spaces
"As a cyclist you have far more freedom to cover space in town. You tend to visit much more businesses because you can, don't have to worry about car parking or how long you're there. You can get from a city centre feeling, hit of fresh air, pop down along the canal very comfortable in amongst the greenery and go back into town"	Facilitating independent mobility for all and developing on-road cycling confidence
	Recognising and maximising the environmental benefits of cycling
	Generating social interactions and building social capital
	Recognising and maximising the health benefits of cycling
	Consumer choice and paying for decisions and modes

(*Continued*)

TABLE 2 Continued

Theme (with supporting quotes)	Sub Theme
Safe and inclusive design and multi-modal solutions	
"it's very frustrating when you are pushed up onto a footpath coming to a roundabout and you have to decide do I get off the bike, do I cross the road as a pedestrian with a bicycle, do you stay on the roundabout even though you've run out of cycle lane"	Access to bike schemes
	Accommodating all users through inclusive and legible design
	Consistent inclusion of groups with specific needs at all planning stages
"My children started cycling when they were about 9 and when they went out the door, my heart was in my mouth. I started cycling with them obviously but they very quickly shrug you off and said they were fine and your heart is in your mouth when they do go off and you teach them the rules of the road and you just hope that someone doesn't hit them because if they get hit by a car, they are vulnerable"	Cycling initiatives aimed at targeted groups
	Dependable public transport routes with clear communication of routes
"wouldn't it be great if the busses had the capacity to put bikes on the back of them"	Integrating with public transport

- Utilise broad stakeholder engagement to identify the leverage points for transformational interventions
- Develop a theory of change framework to cultivate a cycling culture in Kilkenny

The 9-step process was outlined to achieve these objectives.

The functional area of the research was defined as the two electoral areas in Kilkenny City and the electoral area of Kilkenny rural, covering the functional area of Kilkenny city.

The stakeholders were identified as those already involved in the Cycle Kilkenny stakeholder group; Kilkenny Leader Partnership (local development organisation), Chamber of Commerce, Cycling Advocates, the Local Sports Partnership, Disability Access Group and transport representatives from Kilkenny County Council. Additional stakeholders were added so that the group was representative of the entire population. The stakeholder list was reviewed against the quintuple helix model (56), representing government, academia, industry, civil society and the environment and also against the 'Topic Guide- Sustainable Urban Mobility Planning in Smaller Cities and Towns. In response to this, an interdisciplinary team was invited from Kilkenny County Council, representing planning, transport, environment, climate action and tourism. Representatives were also invited from large employers, local traders, the Public Participation Network (representatives of community and voluntary groups) and organisations representing young people.

3.3. Step 3: community based research

Over 50% of respondents lived in Kilkenny City, a further 17% lived within 5k of Kilkenny, a quarter of all respondents lived between 5 and 20k from Kilkenny and just over 5% live greater than 20k from Kilkenny City. Just over 60% of the respondents were female and 60% of all respondents were between 40 and 60 years of age. 90% of respondents owned a car and 66% had two or more cars. Approximately 12% did not have the use of a bicycle.

Almost 90% felt that their community did not have a problem with crime or anti-social behaviour. The vast majority (88%) of the

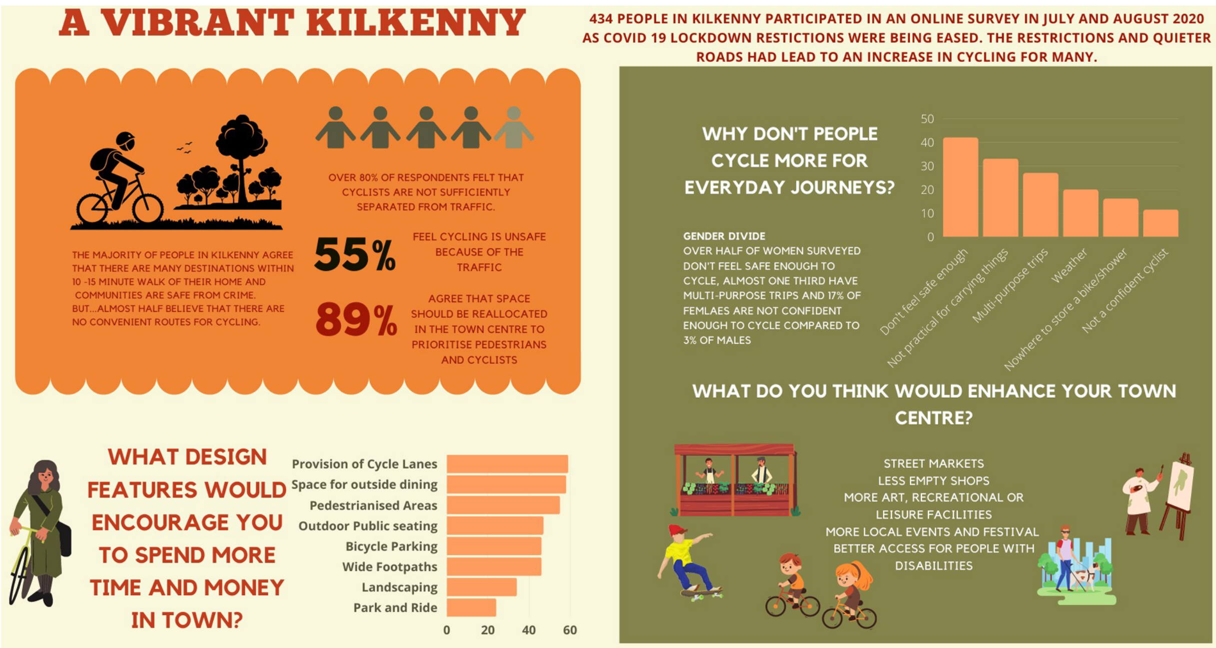

FIGURE 2
Infographic of survey results.

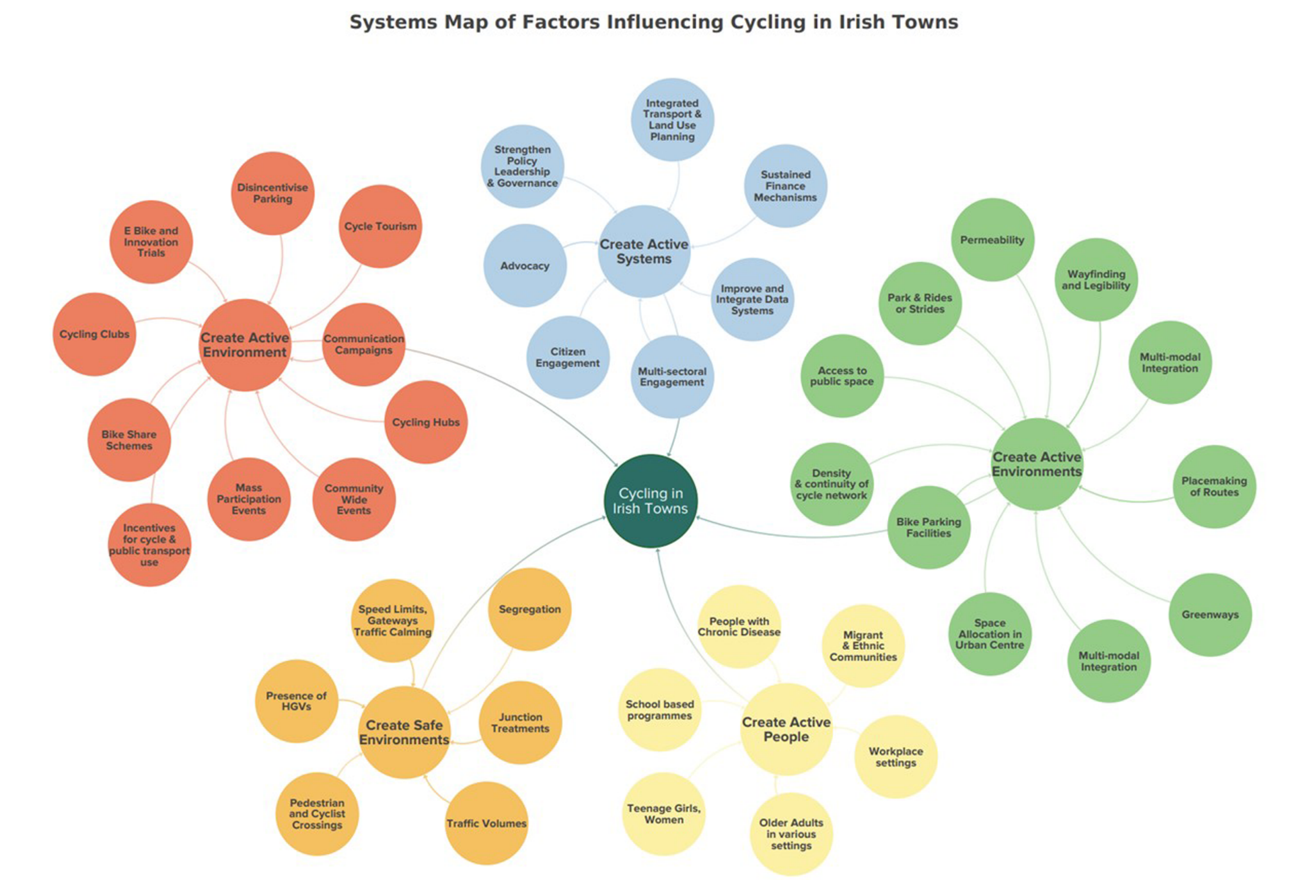

FIGURE 3
Systems Map of factors, represented as elements, influencing cycling in Irish towns.

respondents felt that people in their community can be trusted and almost 70% felt that they knew their neighbours either moderately or extremely well.

When asked about their community and cycling, 55% felt cycling was unsafe because of the traffic and almost half felt that there were no convenient routes for cycling. 82% of all respondents did not agree that cyclists were sufficiently separated from traffic. Five per cent had no interest in cycling, over 40% would like to cycle more and the same number again would like to cycle more if the conditions were right. The most frequently cited barrier was that people don't feel safe enough on the roads. The next three barriers were; not practical for carrying things, journeys are too far and multipurpose trips (transporting children, drop offs etc.).

When asked about their perceptions on cycling, over 90% of all respondents agreed or agreed strongly that people who cycle regularly improve both their health and well-being, that it would be better for the environment if more people cycled and Kilkenny would be a better place if more people cycled. The majority (96%) of all respondents believed that the Local Authority should be investing money in cycling. In spite of the concerns around safety, over half had positive experiences of cycling in Kilkenny but over 17% had never cycled in Kilkenny. The main motivators for cycling were to keep active, get fit or for health reasons and to spend time outdoors followed by environmental reasons.

More than half (55%) of respondents wanted pedestrianised areas in the town centre. Outdoor public seating was also widely looked for. Almost 30% of respondents wanted to see better access for people with disabilities. The biggest changes that respondents would like to see in the town centre were more street markets, less empty shops and more art/recreational or leisure facilities and more small specialised shops. The two most sought-after design features were spaces for outside dining and provision of cycling lanes. Almost 90% of people felt that space should be reallocated in the town centre to prioritise pedestrians and cyclists and 85% felt there were sufficient open spaces in their community. An infographic (see Figure 2 above) summarising the key results was developed and shared with stakeholders and the general public.

3.4. Step 4: stakeholder engagement

A thematic analysis was conducted of the transcripts from semi-structured interviews with seven key stakeholders, three community workshops, and notes and memos from over 50 meetings. The findings of the focus groups were also included in the analysis. The main themes and related subthemes emerging from the inductive thematic analysis are presented in Table 2 above.

Supporting quotes reflecting the meaning of each theme are also included.

3.5. Step 5: systems Map

The final systems map is presented in **Figure 3** above. Causal loops will be presented as part of steps six to nine in a future paper.

4. Discussion

The systems approach adopted for this research allowed for a clear understanding to be gained of the process of change for large, complex systems, specific to cycling in Irish towns. This approach enabled an examination of the interrelationships in the system from multiple perspectives (57). A broad and diverse community and stakeholder engagement identified the key factors that contribute to a cycling culture and informed the development of a context specific systems map. The iteration of the systems map presented in this paper (step 5) contained five strategic objectives with all the factors or variables that influence cycling in Kilkenny depicted as elements on the map. The following section discusses the study findings for each of the broad objectives, considers the merits of using this 9-step systems approach and outlines the next steps in the process.

4.1. Creating active systems

The elements presented under this objective, represent the variables that underpin the system that will allow transformational change to occur. Specifically, there were seven elements which included; policy leadership and governance, integrated transport and land-use patterns, sustained finance mechanisms, multi-sectoral engagement, citizen engagement, advocacy and integrated data systems. Over the last number of decades, our transport systems have been designed in response to the growth in car ownership to facilitate increasing car use resulting in greater allocation of space in urban centres to private cars and the creation of hostile environments for pedestrians and cyclists. This has induced greater car use and car dependency and by favouring the car, urban sprawl and dispersed population patterns have ensued, resulting in reduced active modes (30). The transport system has locked in decades of investments in road infrastructure. Decades of under investment in public transport and active travel has left these modes as unattractive options accounting for small mode shares. There is consensus across stakeholders that the policy framework is now in place. The integration of transport and land use continues to be challenging. In spite of the 10 min city and in-fill policies, population forecasts predict a continuation of traditional, dispersed, settlement patterns. In Kilkenny, although the percentage of forecasted population growth is slightly higher in Kilkenny city, the absolute forecasted growth is just 4,965 compared to 15,268 outside of the two largest urban areas. Remote working may exacerbate this problem, with greater possibilities of residential self-selection. Since 2021, the programme for government has reallocated transport funding to public transport, active travel modes and somewhat less to behaviour change. The focus must move towards scaling up and increasing the pace of implementation and infrastructure roll out. Transformational, systemic change requires multi-sectoral and multi-policy action (58). The establishment of a platform of decision makers with the remit to act on all leverage points in the system is essential to bring about the necessary change. A joined-up approach allows for greater awareness of transport, land use and health challenges in urban centres, across the populations (59, 60). Community members expressed a sense of exclusion from decision making and a desire to contribute to place based solutions, participatory planning and co-creation. On the other hand, a disconnect exists between the work that has been undertaken in the city to date and the awareness of this in the community. There is a need for clear pathways for communication and feedback from the community to decision makers and vice versa. Collaborative work allows for greater understanding of the roles of others and adds value to infrastructure projects by ensuring it recognises and responds to the needs of the communities. Furthermore, an essential part of any systems approach in public health is the improvement and integration of data systems. Indicators must be identified and measurement systems adopted for tracking progress on policies, strategies and interventions (61, 62).

4.2. Creating active and safe environments

Under these two objectives, seventeen elements were identified and the perception of lack of safety was to the fore across all engagements. This is consistent with narratives from other car-dependent countries. Without the provision of safe, segregated cycling infrastructure, cycling is only for "the strong and the fearless", and perhaps "the enthused and confident" (63). The design and development of a strategic cycle network featured prominently together with a reallocation of road space and reduction in traffic volumes and speeds. There are challenges with progressing from the planning to delivery phases for infrastructure projects, investments can face political obstacles and lengthy processes and take many years to deliver (64). Hence, the rapid deployment of cycling infrastructure requires reallocation of road space. Yet, this requires extensive local engagement, placing additional demands on small teams in smaller cities. Extension of car-free centres, one-way systems, filtered permeability, removal of on-street parking and reduction in carriageways is contentious and requires political support. Brave decisions on space reallocations and land use are required. More acceptable, but also long-term solutions include the provision of park and strides/rides, multi-modal hubs, attractive public spaces, green spaces and greenways. Safe, secure bike parking, light segregation, improved crossings and permeability, reductions in speed limits and traffic calming elements can be shorter term solutions and easy wins. This multi-faceted approach to redesigning the built environment is in accordance with other studies (65–67). Additionally, a strong sense of place emerged throughout the engagement process with references to the medieval city, arts and crafts, a strong sporting tradition and the built and natural heritage. There is a desire to weave this into the design of public spaces and mobility networks through placemaking. This is consistent with the findings of the Te Ara Mua Future Streets project (68), that suggests an emphasis on incorporating local traditions into mobility systems can enhance the sense of place and identity. In Kilkenny, this identity extends to the rural hinterland as does the desire for accessible connections to the city. Similarly, Nilsson (69), has suggested that placemaking is an important element in the development of a cycling culture.

4.3. Creating active societies and people

These two strategic objectives contain elements that relate to cultivating a cycling culture in the wider society and under-served population groups and settings. The private car has traditionally been the first choice in Kilkenny with high car ownership and modal share. The lack of alternative mobility solutions was cited frequently in the community engagement and the visibility of other transport options is poor. Cycling is regarded as a crucial element of a multi-faceted solution that views cycling not as a standalone transport mode but as a key piece in the transport offering that is highly dependent on the allocation of space and integration with public transport, park and pedal, micro-mobility and other last mile solutions in smaller cities and towns (16). Leverage points proposed throughout the engagement and also supported in the literature include the provision and availability of bike share schemes and e-bikes, incentives for cycling and public transport use (70, 71) and disincentivising car parking (72, 73). Community-wide programmes such as car-free day, Bikeweek, communication campaigns and mass participation events were also suggested and have a strong evidence base (74, 75). Other propositions included support of cycling initiatives such as cycle tourism, the development of cycle hubs and the support of clubs. Arguably, the leverage points with the greatest potential for modal shift such as disincentivising car driving are often the least feasible to implement.

The elements under Creating Active People were derived from a strong viewpoint that vulnerable road users were not catered for in a car orientated city, resulting in a loss of independent journeys and a disparity in access to social, health, education and employment opportunities. These inequalities associated with access to transport have been reported elsewhere in Ireland (76). To overcome these transport related inequalities in access to services, the system mapping process identified a targeted approach to cycle training and education programmes. This targeted approach for population groups included; people with disabilities and chronic disease, migrant and ethnic communities, teenage girls and women and older adults. To offer localised mobility solutions for the designated target groups and the wider community, the need for workplace and school based programmes were identified. Community wide cycling programmes that deliberately prioritise the needs of vulnerable road users in such a pronounced way are uncommon in the published literature (77, 78).

4.4. Reflecting on the process

Although, it was not a specific objective of the process, the five steps that culminated in the development of a draft systems maps helped create a vision for a cycling city in Kilkenny. The vision is a city that integrates a strategic cycle network with multi-modal provision whilst retaining the rich culture and heritage of the medieval city. The riparian, green spaces provide opportunities for accessible, connective corridors in the city, encouraging active engagement with nature. This vision, if it comes to fruition, will result in a healthier, more liveable city with greater quality of life for all citizens.

The use of a participatory systems approach in this research, allowed for an enhanced engagement process and a detailed mapping of all the variables that influence cycling in Kilkenny and in similar small cities. Subsequently, the mapped variables informed the process of identifying leverage points and involving a broad group of stakeholders in solution generation. In this way, complex problems can be disaggregated, assigned to and analysed by the stakeholders with the expertise, experiences and potential to intervene. The systems approach has resulted in the foundations for an overarching vision, engaged stakeholders and a reservoir of resources to establish a platform to bring about transformational change in the mobility system. A limitation of the systems approach is the greater investment required in the planning stages. Broad stakeholder engagement necessitates additional co-ordination and results in longer preparatory phases. However, the ensuing actions are embedded in local organisations, and are systemic and transformational.

The next steps of this research will focus on utilising this platform to operationalise the systems map. Casual loops will be identified in the systems map. Stocks and accumulations in the system such as car/bike ownership, existing infrastructure and ongoing investment, will be analysed. Interventions will be co-designed with stakeholders and mapped onto a Theory of Change Framework.

5. Conclusion

The paper described how a systems map was developed in a small Irish city utilising broad stakeholder engagement to map the variables that influence cycling in the town and to identify the leverage points for transformational interventions. This work adds to the development of systems approaches to tackle complex problems as it synthesises the scientific evidence, a participatory systems approach and the pragmatic findings of the embedded researcher working alongside an active travel team. The systems map will form the basis of a framework for cultivating a cycling culture in small cities and will take it beyond a theoretical framework to an organic, live process.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by the ethics committee of Waterford Institute of Technology (WIT2021REC014). The patients/participants provided their written informed consent to participate in this study.

Author contributions

CC: conceptualisation, writing—original draft, investigation, data analysis. BL: supervision, conceptualisation, writing, reviewing and editing. NM: supervision, conceptualisation, writing, reviewing and editing. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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TYPE Review
PUBLISHED 29 June 2023
DOI 10.3389/fspor.2023.1157503

Check for updates

OPEN ACCESS

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RECEIVED 02 February 2023
ACCEPTED 16 June 2023
PUBLISHED 29 June 2023

CITATION
Kardan M, Akter T, Iqbal M, Tcymbal A, Messing S, Gelius P and Abu-Omar K (2023) Cycling in older adults: a scoping review. Front. Sports Act. Living 5:1157503. doi: 10.3389/fspor.2023.1157503

Cycling in older adults: a scoping review

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Introduction: Regular physical activity provides many health benefits to older adults. As a well-known form of physical activity, cycling can be an appropriate means for older people to meet WHO recommendations and to improve their health. In addition, cycling can help to protect the environment and reduce greenhouse gas emissions. The primary aim of this scoping review is to identify the currently available scientific evidence and gaps of research in this field.
Methods: A systematic search in seven databases resulted in 7,192 studies. After the exclusion of duplicates, studies were screened by two independent reviewers in a two-stage process. Based on previously defined inclusion criteria, 123 studies were included. Data extraction was based on a descriptive analytical method, and seven categories for the main topics of studies were developed. Data were extracted by three reviewers to analyze different characteristics of included articles such as age range, study design, data type, gender, type of bicycle, and country of origin.
Results: The included studies covered the following topics: (1) traffic safety, (2) cycling as physical activity or for transport, (3) health benefits, (4) environmental factors, (5) facilitators and barriers, (6) application of technology and (7) promotion of cycling. Results show that the majority of studies were performed in both younger (60–79 years) and older (80+ years) adults. Most studies had an observational study design, used conventional bicycles, and were based on quantitative methods. Researchers from the United States, Netherlands, and Japan published the highest number of studies related to cycling.
Discussion: Traffic safety was the most prevalent focus of the included studies. Gaps were identified with regard to studies focusing on the promotion of cycling, application of technology, as well as facilitators and barriers of cycling. While research on traffic safety should continue to be a high priority for public health, potentially more research should focus on how to get older people to bicycle more. This is warranted by the proven individual and planetary health benefits of cycling and the urgency of combating climate change.

KEYWORDS
cycling, older adults, physical activity, safety, active transportation

1. Introduction

Regular physical activity (PA) provides many health benefits to older adults that affect all-cause mortality, cardiovascular diseases, hypertension, cancer, diabetes mellitus type 2, anxiety, depression, cognitive conditions, sleep, the risk of falls and falls-related injuries, bone density, and functional abilities (1). Due to these important health benefits, the World Health Organization (WHO) and national health authorities have adopted evidence-based recommendations on the volume and intensity of PA for different age groups, including older adults (1–3). Despite the well-proven health benefits of PA in older adults, study results from 122 countries show that, across WHO regions, physical inactivity in this age group is more prevalent in comparison to other age groups (4). In addition, according to a systematic review most studies show that between 20% and 60% of older adults fulfill WHO's PA recommendations (5).

As part of PA recommendations, cycling is often recommended for older adults (1, 2). Scientific evidence shows that cycling can be an appropriate training to reduce the fear of falling (6), fat mass, high blood pressure, and cholesterol in older populations (7). It also leads to fitness benefits (8) while improving the overall quality of life (9). From a functional point of view, cycling enhances skeletal muscle power and endurance, gait parameters, general functional performance (10), stepping times, one leg stance, and step response times (11). For achieving these benefits, interventions can use regular (outdoor) or stationary (indoor) bikes. In this review, we focus only on regular bikes and use the term cycling only in this context.

According to available studies, cycling has multiple benefits. For example, a bicycle-based intervention was shown to positively affect metabolic parameters, such as physical fitness level, total fat-free mass, and fasting plasma insulin levels, in rural Indian men (12). Other studies proved that increasing the level of cycling caused a reduction in the total number of road accidents (13, 14). It has also been shown that cycling can reduce the risk of falls (6, 15) and improve the mental health score in older adult populations (16). Furthermore, studies indicate that cycling in older adults can significantly improve participants' happiness, does not cause pain, and is associated with maintaining quality of life (17).

Despite these benefits, there is still potential to increase the number and proportion of older adults cycling. According to a study, 6% of overall urban transportation globally is currently carried out by bicycle, but this percentage could be increased to over 15% by 2050 (18). Another study showed specifically for older adults that 12%–24% of trips are made by bicycle in Germany, Denmark, and the Netherlands (19). In the United States, however, the overall percentage of bicycle use is comparatively low (1%), and older adults are the age group least likely to use a bicycle (20). Another study asserted that there is currently an increasing trend towards bicycle use in the United States (21).

A primary concern for older individuals has been the safety of cycling in order to avoid injuries and crashes (22), particularly as older populations have higher rates of cycling accidents (23). Some authors (24, 25) have highlighted safety and traffic as the most important concerns regarding cycling in older adults. Both cycling infrastructure (26, 27) and the built environment in general (28–33) have been shown to affect cycling behavior in older adults. Although cycling is generally highly recommended and is considered an advantageous way of transportation, most individuals choose other types of transportation. This holds true even in the Netherlands, a country with a highly developed cycling infrastructure and well-known tradition of cycling (34).

It has been suggested that psychological (35, 36), personal, and social (37) factors may facilitate or hinder cycling in older adults. To overcome such barriers, active strategies to promote cycling among older adults need to be developed. This is particularly important as cycling is not only a way to improve public health (8) but also a means to reduce pollution and greenhouse gases (38) and to support climate action (39, 40). The WHO's Global Action Plan on PA describes cycling as a "key means of transportation" that enables "regular PA on a daily basis" (1). Several interventions to promote cycling have been shown to be effective (41), and public transport policies, such as the development of infrastructures and active travel programs, can increase population PA levels (42). This research is complemented by success stories from cities that managed to increase bicycle use, for instance by integrating cycling into public transport, increasing the cost of car use, and clarifying cyclists' legal rights (43, 44).

However, there is currently a limited understanding of what research in the interdisciplinary field of cycling looks like in its entirety and how well it aligns with the potential of cycling as a means of PA promotion. Therefore, we conducted a scoping review that intends to complement existing reviews that focus on specific aspects of cycling, such as the links between the physical environment and active travel in older adults (45).

2. Method

This scoping review was conducted based on the framework developed by Arksey and O'Malley (46) and expanded by Levac et al. (47). The review included five key stages: (1) Identifying the research question, (2) identifying relevant studies, (3) study selection, (4) charting the data, and (5) collating, summarizing, and reporting the results. The optional sixth stage "consulting with stakeholders to inform or validate study findings" was not conducted.

2.1. Identifying the research question

This review aims (a) to scope the available evidence on cycling in older adults to identify its main topic as well as potential gaps in this field of research and (b) to analyze the included articles in terms of age range, study design, data type, gender, type of bicycle, and country of origin. The review focuses solely on general/outdoor cycling, as stationary indoor cycling is substantially different in terms of environmental conditions, biomechanics of pedaling, safety, feasibility, and physiological or psychological response (48–52).

2.2. Identifying the relevant studies

We searched for studies related to cycling in older adults published in English and German before December 22nd, 2021. The search for relevant studies was performed in seven databases: PubMed, Web of Science, Scopus, Cochrane library, SportDiscus, CINAHL, and PsychInfo. The search strategy was developed by all authors and consulted with a librarian. The search strategy included the following keywords related to

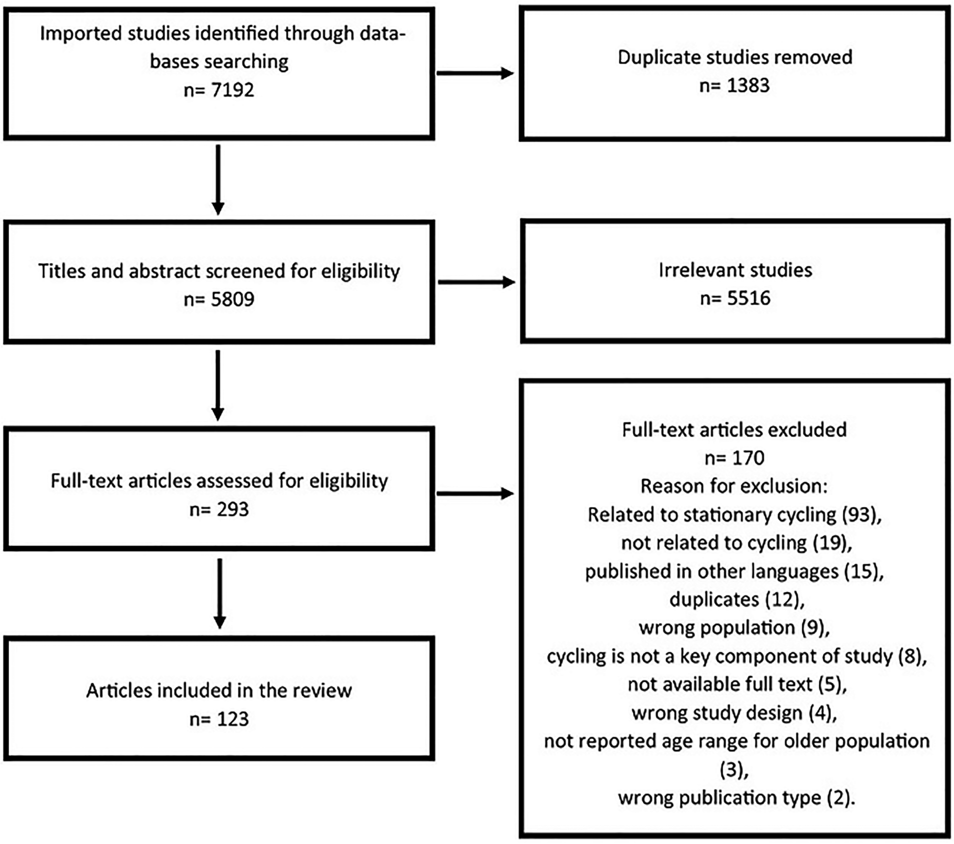

FIGURE 1
Study selection.

cycling in older adults: (“old people” or “older people” or “elderly” or “elders” or “aging” or “ageing” or “old men” or “old women” or “older persons” or “older adults” or “seniors”) and (“bicycling” or “cycling” or “biking” or “bike” or “bicycle”). A combination of different MeSH terms and free text was used to search databases.

2.3. Study selection

Records were managed in the Covidence systematic review software (www.covidence.org). Duplicates were removed automatically. The screening process involved two stages based on inclusion and exclusion criteria. In the first stage, articles were screened by title and abstract, while the second stage included selection of studies by reading the full texts. The inclusion criteria were:

1. The study includes human subjects aged 60 years and/or older.
2. Cycling is one of the main components of the study or the study objective is related to cycling (general/outdoor cycling).
3. The study investigates one or more of the following:
   - the health effects of cycling,
   - injuries and/or risk of injuries caused by cycling (aspects of safety),
   - factors that determine if a person bicycles outdoors and/or the prevalence of cycling,
   - the promotion of cycling for health reasons.
4. The study was published in a peer-reviewed journal (study protocols, letters, commentaries, and conference abstracts were excluded).
5. Cycling was not used as a means to investigate a different purpose of study, e.g., to test endurance, heart rate, the training effects of cycling, or as a warm-up.

Figure 1 shows the stages of the search and retrieval processes of this study. The database search resulted in 7,192 studies. After removing duplicates, 5,809 studies remained. Three reviewers screened titles and abstracts, and each study was screened independently by two reviewers (MK, TA, & ME). Disagreements between the reviewers were discussed until a consensus was reached.

After title and abstract screening, the full texts of 293 references were further screened to determine their eligibility for inclusion. Each study was screened independently by two reviewers (MK & TA), and conflicts were discussed until a consensus was reached. To avoid bias, reviewers used the internet-based software Covidence, which provides random access to articles for reviewers.

2.4. Charting the data

A descriptive analytical method (53) was used as a basis for developing categories to structure the included studies according to their main topic. Categories were developed by a multidisciplinary group consisting of all authors (with expertise in sociology, political science, physiotherapy, medicine, and psychology) through regular meetings and discussions. Studies could be assigned to more than one category. Data extraction included the following items: title, author name, year of publication, country of origin, gender of population, study design (observational studies, interventional studies, reviews), main topic of study, type of bicycle (conventional outdoor bicycle, e-bike, pedelec), type of data gathering and analysis (qualitative, quantitative, or mix of both), and age range of the population.

3. Results

3.1. Reviews

One review was identified. In this systematic review and meta-analysis, the neighborhood physical environment and active travel in older adults were analyzed based on 42 quantitative studies. The results show that there are strong links between the neighborhood's physical environment and active travel in older adults. In particular, the review identified positive associations with total walking for residential density/urbanization, walkability, street connectivity, access to destinations/services, land use mix, pedestrian-friendly features and access to several types of destinations (45).

3.2. Single studies

The study characteristics of the 122 single studies are presented in Table 1. Out of these studies, 107 (87.70%) focused on all older adults (60 years old and over) and 15 (12.30%) on the lower age range of this population (60–79 years old). There were three (2.46%) studies focusing specifically on men, six (4.92%) on women, and 113 (92.62%) on both genders. 114 studies (93.44%) were based on an observational study design and eight (6.56%) were interventional (experimental). 109 studies (89.34%) were based on quantitative data, seven (5.74%) on qualitative data, and six (4.92%) mixed quantitative and qualitative data. 109 studies (89.34%) were related to only conventional outdoor bicycles, four (3.28%) to only e-bikes/pedelecs, and nine (7.38%) to both conventional outdoor bicycles and e-bikes/pedelecs.

TABLE 1 Characteristics of 122 included studies.

Characteristics of studies	Number of studies (*n*), percentage (%)
Age range	
Only younger older adults (60–79 years old)	15 (12.30%)
Only older older adults (80 years old and over)	0 (0.00%)
All older adults	107 (87.70%)
Study design	
Observational studies	114 (93.44%)
Interventional studies	8 (6.56%)
Data type	
Quantitative	109 (89.34%)
Qualitative	7 (5.74%)
Mixed method	6 (4.92%)
Gender	
Both genders	113 (92.62%)
Women only	6 (4.92%)
Men only	3 (2.46%)
Type of bicycle	
Only conventional bicycle	109 (89.34%)
Only e-bike	4 (3.28%)
Both conventional and e-bike/pedelec	9 (7.38%)

Figure 2 shows the main topics of studies. The majority of publications were related to traffic safety, including the use of cycling helmets with 68 studies (55.74%), followed by cycling as PA and a means of transport with 34 studies (27.87%), the health benefits of cycling with 14 studies (11.48%), environmental factors with eleven studies (9.02%), facilitators and barriers of cycling with seven studies (5.74%), the application of technology with two studies (1.64%), and the promotion of cycling with one study (0.82%).

Figure 3 illustrates the growing number of publications over time. For each category, the highest number of new publications was identified for the period 2013–17 or 2018–21. Across all categories, 99 (81.15%) of the included studies were published in the last decade (2013–2021).

Figure 4 shows the number of published studies by country. The United States (24 studies), the Netherlands (21 studies), and Japan (twelve studies) had the highest number of publications, followed by Canada and Sweden (eight studies each), Belgium (seven studies), Germany (six studies), Australia and South Korea (five studies each), Taiwan (four studies), Denmark (three studies), China, Italy, and Spain (two studies each), and Austria, Brazil, Croatia, England, Finland, Greece, Iran, Israel, Norway, Poland, Singapore, Switzerland, and Thailand (one study each).

Table 2 shows the main topics of studies for the top three countries (United States, The Netherlands, Japan) in terms of quantity and contents of publications. The highest number of published studies in the United States and the Netherlands were related to traffic safety, while the highest number of studies from Japan was related to cycling as PA or for transport. The United States and the Netherlands had four and three studies on health benefits, respectively, while Japan had no study on this topic. The Netherlands had three studies related to environmental factors affecting cycling, and the United States and Japan had

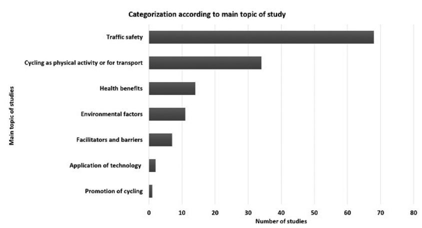

FIGURE 2
Categorization of studies on base of main topics of study.

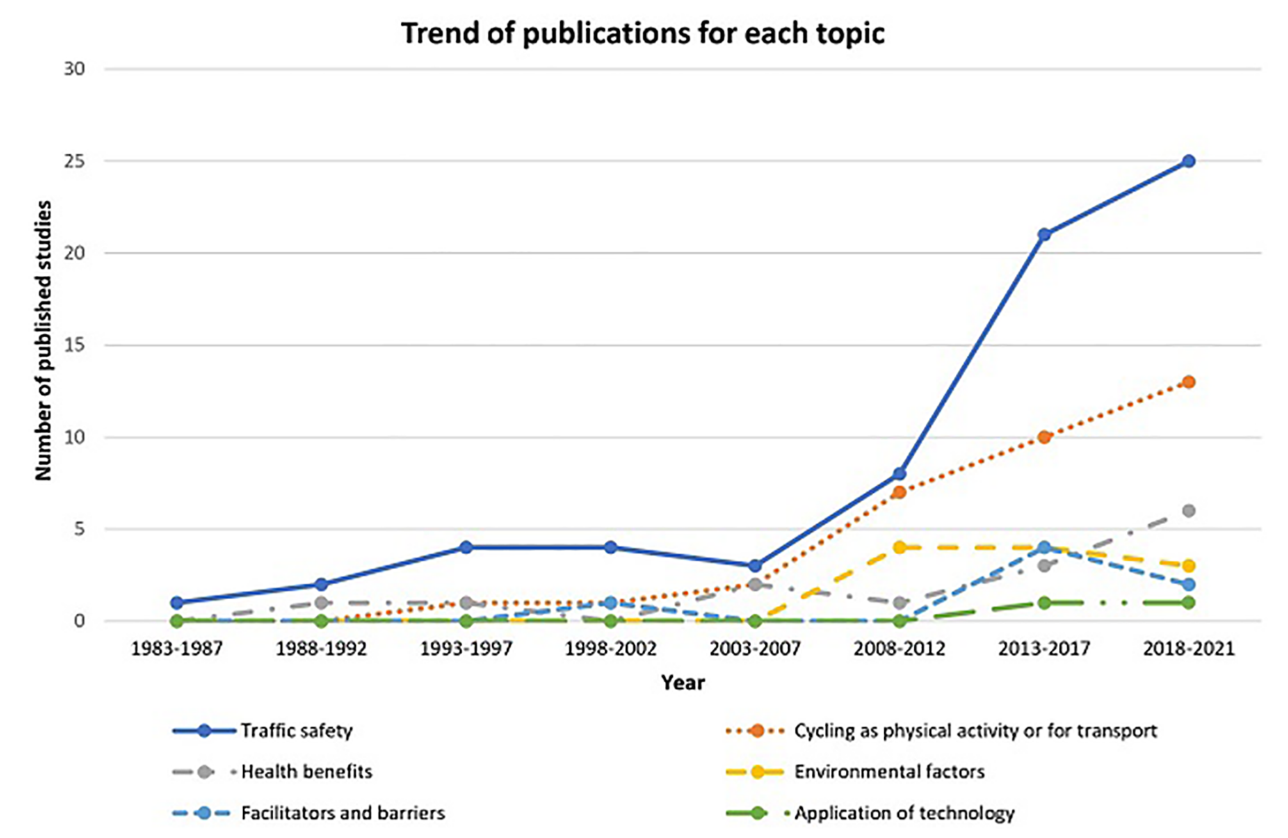

FIGURE 3
Trend on published studies during the time.

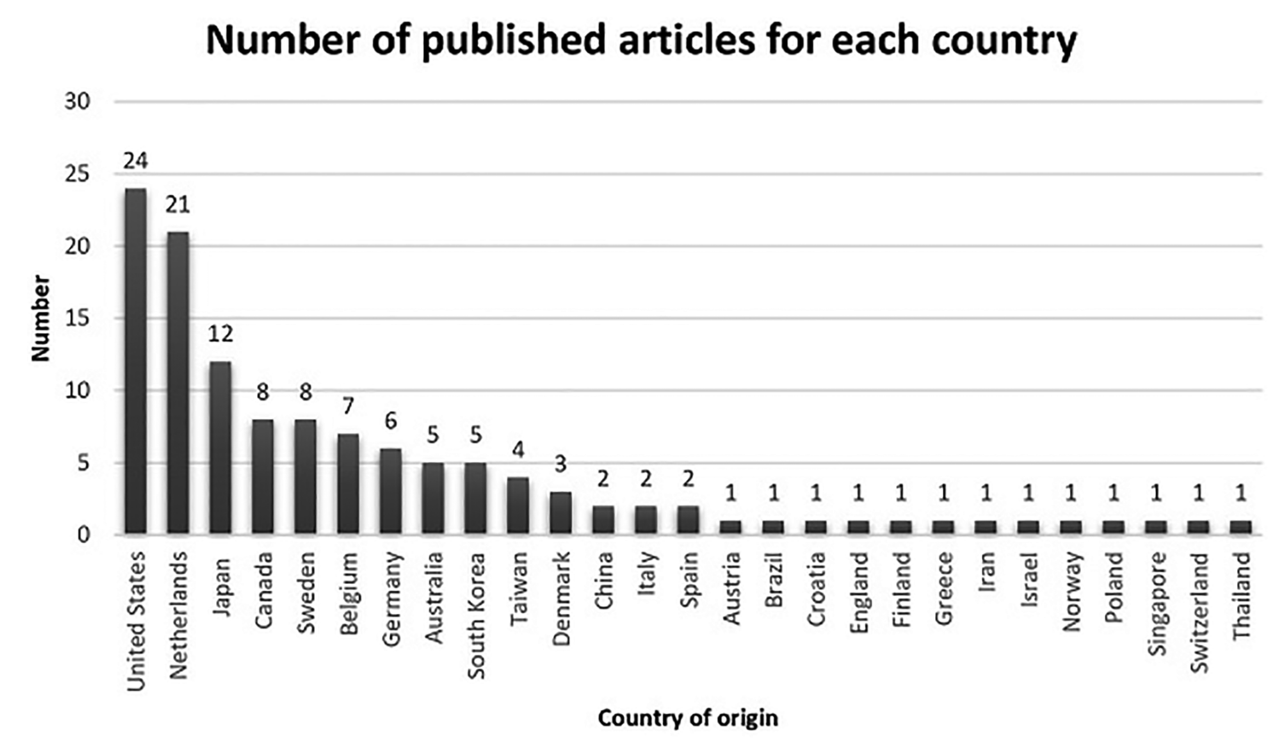

FIGURE 4
Number of published studies per country.

TABLE 2 Main topics of studies published in United States, The Netherlands, and Japan.

Main topic of study	United States	The Netherlands	Japan
Traffic safety	14	11	5
Cycling as physical activity or for transport	5	5	7
Health benefits of cycling	4	3	0
Environmental factors	1	3	1
Facilitators and barriers of cycling	1	0	0
Application of technology	0	2	0
Promotion of cycling	0	0	0

one study each focusing on this topic. Regarding facilitators and barriers, there was one study from the United States and no studies from the Netherlands and Japan. With regards to the application of technology, the Netherlands had two studies, while the United States and Japan had no studies on this topic. Moreover, none of the three countries had a study focusing on the promotion of cycling.

4. Discussion

4.1. Summary

The primary objective of this scoping review was to identify studies dealing with cycling in older adults. Overall, 123 studies were identified, most of which used observational designs, while there were few intervention studies and only one review. The studies could be categorized as pertaining to seven main topics, with more than two-thirds focusing on traffic safety. Other topics investigated more frequently include cycling as PA or for transport, health benefits, and environmental factors. By country, almost half the studies were conducted by research teams located in the United States, the Netherlands, and Japan. Time series analysis indicates that research interest in cycling among older people increased markedly after 2007.

4.2. Research perspectives on cycling among older adults

We observed a heightened interest in the safety aspects of cycling (24, 25, 54). By contrast, only one of the included studies dealt with the promotion of cycling among older people. This is surprising, especially when one considers that active transport (cycling and walking) has been shown to have numerous health benefits (1, 6, 7, 10, 11) and can contribute to people reaching recommended PA levels (1, 2). In addition, cycling has important environmental co-benefits (38, 40). People who engage in active transport rather than using a motorized vehicle help reduce air pollution in cities (38). Cycling in cities has also been associated with making cities safer and improving the self-reported quality of life of residents (9, 14). Likewise, from an economic point of view, a study focusing on the European Union showed each kilometer driven by car causes external costs of €0.11, while cycling represents benefits of €0.18. Also, the costs of automobility are about €500 billion per year, while the positive health effects of cycling amount to external benefits worth €24 billion per year (55).

Evidence has shown a positive association between the extent of cycling paths and non-recreational cycling (56). Environmental factors such as presence of cycling routes or paths, separation of cycling from other traffic, high population density, short trip distance, and proximity of cycling paths or green spaces are positively associated with cycling (57). These studies suggest that cycling can be promoted as a cheap way of transportation by investing in infrastructures.

Currently, prevalence rates of cycling among older people are quite low in many countries, and even in bike-friendly countries only a minority of older people report to cycle regularly (34). In France, it has been demonstrated that increasing the uptake of cycling among older people would support efforts to lower carbon emissions and adherence to the Paris Agreement (58). It can be assumed that the same might hold true for other nations. As such, the results presented here serve as a call to increase research efforts on how to promote cycling among older people. While research on safety issues should continue to be a high priority for public health, this should not deter scholars from conducting more research on how to get older people to cycle more. After all, research has shown that, the more people use bicycles, the safer cycling becomes for everybody involved (14).

4.3. Country differences in research on cycling among older adults

The majority of studies were conducted in high-income countries such as the United States, the Netherlands, or Japan. Among these three, the Netherlands is most prominently associated with being a “bicycling country” (59), hinting that the rate of cycling in a given country might not be able to fully explain who is engaging in research on this topic. Notably in this regard, two other countries often named as cycling-friendly countries—Denmark and Germany—have produced only a limited amount of research on this topic.

However, it seems to be highly relevant to conduct more research on cycling among older adults in low- and middle-income countries. It is a general problem of PA-related research that there is a large gap in the number of publications between high- and low-income countries (60). From a global health perspective (61, 62) this raises the question whether the available evidence is even applicable to low- and middle-income countries, which might not necessarily have an appropriate cycling infrastructure. Furthermore, geographical, political, or cultural differences might require specific research on cycling in these countries.

4.4. Policy context

The results indicate that research on safety issues regarding cycling is important. Also, from a political perspective, the importance of road safety in the context of PA promotion is reflected in documents such as WHO's Global Action Plan on Physical Activity (WHO 2018) and its European Physical Activity Strategy (WHO 2016). These documents call for the implementation of policy actions to improve the safety of cyclists (WHO 2018) and for identifying linkages between PA promotion and road safety strategies (WHO 2016). In addition, policy documents highlight the importance of a cycling network infrastructure (WHO 2016, 2018), pre- and in-service training of professionals in the transport sector on PA promotion (WHO 2018), and the removal of barriers for disadvantaged groups (WHO 2016). An in-depth analysis of the identified studies on facilitators and barriers of cycling for older adults could help to identify target group-specific barriers for cycling and develop appropriate strategies to remove them.

4.5. Limitations

This study was limited to published studies in English or German, and including studies written in other languages might have changed the nature of the results. Also, we acknowledge that the categorization of the identified studies by research topic was not always easy, since some studies covered more than just one topic (e.g., environmental factors and facilitators/barriers). Furthermore, this review focused exclusively on scientific studies and did not include other types of publications, such as policies and intervention reports, that may also serve to promote cycling among older adults.

4.6. Conclusion

To our knowledge, this is the first scoping review in the field of cycling in older adults which covers a broad range of articles in order to identify the state of the evidence on cycling in older adults. Traffic safety was the most prevalent topic of the included studies. The number of studies being published has increased over time, but the rate of increase for each main study topic was different. For some topics, such as the promotion of cycling and health benefits, only a few published studies were identified despite their well-documented importance. The majority of studies were conducted in a small number of countries. Studies from additional countries and world regions may be required to account for different geographical, infrastructural and cultural contexts. Moreover, for some study topics, such as environmental factors, facilitators and barriers, application of technology, and promotion of cycling, only a few published studies were identified, warranting further attention to these topics in future research. The growing tendency towards ownership and use of e-bikes, pedelecs, and recumbent bicycles, also seems to call for conducting more research in these fields. In addition, given the very low numbers of qualitative and review study designs identified in this paper, further research using non-quantitative designs may enrich the evidence on how to promote cycling. Finally, most studies had observational study designs, while only a few interventional studies were conducted. The urgent need to promote cycling requires more interventional studies to produce evidence on how to provide ideal conditions for cycling and maximize the desired effects.

Author contributions

All authors contributed to study conceptualization and design. MK, TA, and MI conducted the literature search and title/abstract screening. MK and TA screened the full texts. MK analyzed and interpreted the results. MK, TA, and MI wrote the original manuscript draft. AT, SM, PG, and KA-O critically revised the manuscript. All the authors contributed to the article and approved the submitted version.

Funding

We acknowledge financial support by Deutsche Forschungsgemeinschaft and Friedrich-Alexander-Universität Erlangen-Nürnberg within the funding programme "Open Access Publication Funding".

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fspor.2023.1157503/full#supplementary-material

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TYPE Review
PUBLISHED 19 September 2023
DOI 10.3389/fspor.2023.1168357

OPEN ACCESS

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RECEIVED 17 February 2023
ACCEPTED 05 September 2023
PUBLISHED 19 September 2023

CITATION
Logan G, Somers C, Baker G, Connell H, Gray S, Kelly P, McIntosh E, Welsh P, Gray CM and Gill JMR (2023) Benefits, risks, barriers, and facilitators to cycling: a narrative review. Front. Sports Act. Living 5:1168357. doi: 10.3389/fspor.2023.1168357

Benefits, risks, barriers, and facilitators to cycling: a narrative review

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There is large potential to increase cycling participation worldwide. Participation in cycling is associated with lower risk of mortality from any cause, and incidence of cardiovascular disease and type 2 diabetes, as well as positive mental health and well-being. The largest potential for health gains likely to come from increasing participation amongst those who do not currently cycle regularly, rather than encouraging those who already cycle regularly to cycle more. Replacing car journeys with cycling can lead to reductions in air pollution emissions and lower pollutant exposure to the general population. Important gaps and uncertainties in the existing evidence base include: the extent to which the health benefits associated with cycling participation are fully causal due to the observational nature of much of the existing evidence base; the real-world economic cost-benefits of pragmatic interventions to increase cycling participation; and the most effective (combination of) approaches to increase cycling participation. To address these uncertainties, large-scale, long-term randomised controlled trials are needed to: evaluate the effectiveness, and cost-effectiveness, of (combinations of) intervention approaches to induce sustained long-term increases in cycling participation in terms of increases in numbers of people cycling regularly and number of cycling journeys undertaken, across a range of population demographic groups; establish the effects of such interventions on relevant outcomes related to health and wellbeing, economic productivity and wider societal impacts; and provide more robust quantification of potential harms of increasing cycling participation, such as collision risks.

KEYWORDS
cycling, physical activity, active travel, public health, economic

1. Introduction

Established causal relationships between general physical activity and health outcomes are well documented (1, 2). While riding bicycles is often included in population measures of physical activity alongside other exercise modalities, few studies have investigated the contribution of cycling alone with health associations (3). Cycling can be performed for leisure, sport, commuting, active transport and utility (e.g., shopping, school run), however quantification of precise contributions of cycling purpose to health are not well known (4). Despite this, cycling is increasingly forming an important component of public health recommendations and active transport policy, but uncertainty still exists about the effectiveness of intervention strategies to improve cycling (5).

This narrative review intends to provide a balanced, evidence-based, overview of the benefits and risks of cycling and the potential scope of consequences of increasing cycling participation for health, wellbeing, the environment, and the economy, as well as providing an overview of the evidence about barriers to cycling, and approaches which have been tried so far to increase cycling participation. Throughout, we aim to summarise what is known on each of these topics and to highlight the key evidence gaps and to outline the next steps needed to address these gaps. In doing so, we provide a clear pathway, outlining the work still needed, to facilitate the goal of a sustained increase in cycling uptake globally.

2. The benefits of cycling on physical health outcomes

For outcomes where relevant systematic reviews and meta-analyses have been published, findings from these analyses have been reported. These have been updated with of evidence from more recent studies published since these reviews reported as appropriate. In areas where a systematic review or meta-analysis has not been published, we have attempted to report a representative overview of the available data. The available evidence on cycling and specific health outcomes is summarised in the sections below.

2.1. Cycling and risk of mortality

The available evidence from large prospective cohort studies indicates that regular cycling is associated with a lower risk of mortality. In 2014, Kelly et al. published a comprehensive systematic review and meta-analysis collating evidence from all published studies in healthy adults investigating the association between participation in cycling and risk of mortality (3). This analysis included data from seven large scale studies—four from Denmark, two from the United Kingdom, and one from China—which included approximately 200,000 adults aged from 20 to 93 years, and over 2 million person-years of observation. In these studies, participation in cycling was assessed and participants were followed up for between 5.7 and 18 years with mortality outcomes over this follow-up period recorded. The data were statistically adjusted for a range of potential confounding factors. All studies performed adjustment for age, smoking, other non-cycling physical activity, at least one indicator of socio-economic status, and aspects of health status, and either adjusted for sex or performed analyses in single sex groups. Four studies also adjusted for body mass index, and three studies adjusted for alcohol intake. Key features of the studies included in the 2014 Kelly meta-analysis (3) are outlined in **Supplementary Table S1**.

All but one study reported that higher levels of cycling were associated with a lower risk of mortality over the follow-up period. When data from all studies were combined, there was a clear, statistically significant lower risk of mortality associated with regular cycling participation. The combined data from all of these studies, illustrated in **Figure 1**, indicated that higher levels

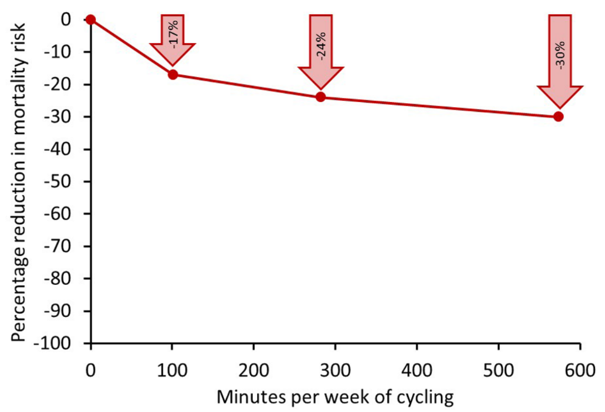

FIGURE 1
Relative reduction in risk of mortality associated with different weekly volumes of cycling compared with undertaking no regular cycling for a meta-analysis of seven large-scale population studies. Data in individual studies adjusted for a range of confounding factors including age, sex, smoking, other non-cycling physical activity, socio-economic status, and aspects of health status. Points on graph at 100, 280 and 570 min per week represent the mid-points of ranges of 10–210, 210–350, and 350–800 min per week, respectively. Modified from (3).

of cycling were associated with lower risk of mortality with a curvilinear relationship, with the largest difference in mortality risk being between individuals reporting no cycling and those reporting undertaking up to approximately 100 min per week of cycling. Participation in approximately 100 min of cycling per week was associated with a 17% lower risk of mortality compared with no cycling participation, in analyses adjusted for major confounding variables.

Levels of cycling beyond this range were associated with a further lowering of mortality risk, but the risk reduction was less steep. Participation in approximately 270 min per week was associated with a 24% lower mortality risk compared with no cycling, however, participation in approximately 570 min per week was associated with a 30% lower risk of mortality compared with no cycling. The clear implication of this is that bigger public health gains will be realised by encouraging individuals who currently do not cycle regularly to do some cycling, rather than getting those who currently cycle regularly to cycle more.

Since the publication of the Kelly et al. (2014) systematic review and meta-analysis (3), further epidemiological studies have examined the association between cycling participation and risk of mortality. Key features of these studies are summarised in **Table 1** and described below.

Koolhaas et al. examined the association between cycling participation and risk of all-cause mortality amongst 7,225 older adults (mean age 70 years) in living in Rotterdam, who were followed up for a median of 13.1 years (6). They reported that participation in "medium" levels of cycling (median 13 min per day, or 91 min per week) was associated with an 28% lower risk of mortality compared with no cycling participation, after adjustment for confounders (**Supplementary Table S2**), and participation in "high" levels of cycling (median 51 min per day

TABLE 1 What is known and what is not yet know about barriers to cycling.

Barriers to cycling		
What is known	**What is not yet known**	**What is needed to fill evidence gap**
Key barriers to cycling include:		
• Local environment ○ Lack of cycle route/paths ○ Hills ○ Distance to travel ○ Weather • Facilities ○ Lack of secure cycle parking ○ Lack of showers at work (after effortful cycling) • Individual factors ○ Perceived lack of safety ○ Perceived attitude of other road users ○ Convenience of using car ○ Lack of skills ○ Lack of confidence ○ Cost ○ Lack of time due to family, work and social commitments ○ Lack of interest in cycling as a 'sport'	• Which of the identified barriers to cycling are amenable to change? • Which interventions to reduce barriers are feasible/acceptable/effective? • What are specific barriers to cycling for older adults and how might these be overcome? • What are specific barriers to cycling for different disabilities, and how might these be overcome? • What are specific barriers to cycling for different BAME groups and how might there be overcome? • What are specific barriers to recreational cycling, and how might they be overcome?	• Systematic reviews of the available evidence on barriers to cycling in older adults, specific disabilities and specific BAME groups • Cross-sectional studies on barriers to cycling in these groups • Cross-sectional studies focusing specifically on barriers to recreational cycling • Qualitative studies to examine attitudes and experiences of barriers to overcoming cycling in different population groups and different contexts (e.g. high cycling infrastructure vs. low cycling infrastructure, rural vs. urban, high socioeconomic status vs. low socioeconomic status) • Development and testing of interventions to overcome identified barriers in different populations groups and different contexts.

or 357 min per week) was associated with an 35% lower risk of mortality.

To minimise the potential contribution of reverse causality, Koolhaas et al. undertook sensitivity analyses where they excluded deaths occurring in the first 5 and first 10 years of follow up (those with pre-existing disease are more likely to die within the first few years the measurements), and the findings were essentially unchanged (6). This is an important study as it focused on older adults, where there had previously been limited data, and shows that the associations between cycling participation and lower risk of mortality extend into older age. Importantly, the findings are consistent with the Kelly et al. meta-analysis which reported the largest reduction in mortality risk when moving from undertaking no regular cycling to a undertaking approximately 100 min per week with diminishing further returns thereafter (3).

In a large-scale study of 80,306 UK adults followed up for 9.2 years, Oja et al. found that participation in any compared to no cycling was associated with a 15% lower risk of mortality, after adjustment for confounders (7). Interestingly, this analysis revealed no clear effect of self-reported cycling intensity or weekly cycling duration on the association between cycling and mortality, which again is consistent with the findings from the Kelly et al. meta-analysis (3), which indicated that the largest benefit in terms of lowering of mortality risk was observed when moving from no cycling to some cycling.

In the largest study to date of cycling participation and risk of mortality—approximately the size of all previous studies combined—Celis-Morales et al. examined the association between mode of commuting to work and risk of mortality amongst 263,540 participants in the UK Biobank cohort who were followed up for 5 years (8). Compared with non-active commuting (car/motor vehicle or public transport), cycling to work was associated with a 41% lower risk of mortality. Mixed-mode commuting, where participants undertook part of the journey by cycle with the remainder using a non-active form of transport, was associated with a 24% lower risk of mortality. This is an important finding which indicates that for individuals who live too far from work to cycle the whole way could potentially gain substantial benefits from cycling part of the way. There was a dose-response relationship between weekly cycling commuting distance and risk of mortality, with those commuting less than 30 miles per week having 32% lower risk of mortality, compared to non-active commuters, and those cycling more than 30 miles per week to work having a 40% lower mortality risk. Again, this non-linear response with the largest difference in risk seen between no cycling and some cycling, rather than some cycling and more cycling is consistent with the findings of the Kelly et al. meta-analysis (3).

Finally, in a large study of the combined effects of physical activity and air pollution amongst 52,061 older Danish adults living in urban environments, Anderson et al. reported that participation in cycling was associated with a 17% lower risk of mortality and this association was not modified by exposure to high levels of traffic-related air pollution (9).

Thus, in summary, a large body of epidemiological evidence, including data from over half a million participants has consistently demonstrated that participation in regular cycling is associated with lower risk of mortality compared with no cycling. The curvilinear nature of the dose response relationship (**Figure 1**) indicates that that the largest benefit is seen when moving from no cycling to some cycling. Thus, with a large proportion of the population cycling less than this amount, it is clear that to maximise public health gains, it is necessary to focus on increasing participation amongst those who do not currently cycle regularly, rather than encouraging those who already cycle regularly to cycle more.

2.2. Cycling and risk of cardiovascular disease

There is a large body of robust data from prospective cohort studies (approximately 50 studies with a total of over 700,000 participants) that participation in physical activity is associated lower risk of incidence and mortality from cardiovascular disease (CVD) and coronary heart disease (CHD) (10–14), with a curvilinear dose response relationship, similar to that observed for all-cause mortality (**Figure 1**).

A smaller number of studies have specifically examined the association between cycling participation and incidence or mortality from CVD or CHD (7–9, 15–23). These studies are summarised in **Supplementary Table S3**. Of the 12 studies identified, including over 700,000 participants, five were from Denmark, four from the UK, and one each from Netherlands, USA and China. Eleven out of 12 studies reported numerically lower risk of CVD or CHD with higher levels cycling of participation (7–9, 15–17, 19–23); in six of these studies this association was statistically significant (8, 9, 16, 17, 22, 23).

Most studies focused on primary prevention and excluded participants with CVD or CHD at baseline. One study considered both primary prevention and secondary prevention data (22), reporting that participation in cycling was associated with lower risk of both a first myocardial infarction (heart attack) and of a subsequent myocardial infarction in those who had already had an event. It seems likely that the lack of a statistically significant association in some of the studies which suggested numerically lower CVD or CHD risk amongst cyclists (7, 15, 19–21)may reflect insufficient statistical power to robustly detect an association, rather than the absence of benefit. However, the directional consistency of the findings suggests that if a meta-analysis was undertaken combining all the available data, an overall statistically significant association between cycling participation and lower risk of CVD and CHD would likely be observed.

2.3. Cycling and risk of cancer

Studies which have considered the association between cycling specifically and cancer incidence and mortality amongst populations who did not have cancer at baseline are summarised in **Supplementary Table S4**. Studies examining the association between physical activity and survival from cancer in cancer patients were not considered. Nine studies were identified (8, 9, 15, 16, 19, 20, 24–26) investigating the association between cycling participation and cancer. Two studies reported that participation in cycling was associated with lower risk of overall cancer incidence and mortality (8, 20), but others did not observe a statistically significant association between cycling participation and cancer risk (9, 15, 16, 19). Cycling was associated with lower risk of lung cancer in women but not in men (26), but was not associated with significantly lower risk of colon cancer (24) or prostate cancer (25). Thus, the available evidence on cycling and risk of cancer is mixed and further larger studies with sufficient statistical power to robustly assess effects of cycling on incidence of specific cancers are needed.

2.4. Cycling and risk of type 2 diabetes

A number of cross-sectional studies have indicated that participation in cycling is associated lower prevalence of type 2 diabetes (8, 27–30), but relatively few prospective cohort studies have investigated whether cycling participation amongst those who are free from type 2 diabetes at baseline is associated with lower incidence of developing the disease. These studies are summarised in **Supplementary Table S5**.

Rasmussen et al. (31) evaluated the effects of cycling participation on incidence of type 2 diabetes in 52,513 Danish adults aged 50–64 years at baseline and followed up for 14.2 years. Cycling participation was assessed by self-report questionnaire at baseline, then again approximately 5 years later. This study showed that increasing levels in both total cycling and commuting cycling were associated with lower risk of type 2 diabetes in a curvilinear dose-dependent manner with the greatest benefit seen when comparing those participating no cycling to some cycling, analogous to the relationship seen between cycling and all-cause mortality (see **Figure 1**). It also observed that individuals who did not cycle at baseline, but had initiated cycling by the second assessment had a 20% lower risk of developing type 2 diabetes than those who were consistently non-cyclists, showing that initiation of cycling even in mid-to-late adulthood was associated with benefit. Interestingly, year-round cycling was associated with lower risk of type 2 diabetes than cycling in summer or winter only, emphasising the importance of cycling consistently throughout the year for maximal risk lowering.

An earlier study of 70,658 Chinese women aged 40–70 years followed up for 14.6 years by Villegas et al. (32) reported that participation in cycling was associated with a 19% lower risk of developing type 2 diabetes, but this was attenuated to a 14% lower risk in a sensitivity analysis which excluded participants with coronary heart disease, stroke, cancer at baseline.

Hu et al. (33)undertook an analysis of 70,102 US Nurses aged 40–65 years at baseline and followed-up for 8 years, finding that participation in any cycling was associated with a non-significant 4% lower risk of type 2 diabetes. However, it is important to note that this analysis used relatively crude measure of cycling participation (any vs. none) and the reported risk estimate was after adjustment for all other physical activities which were more robustly quantified than cycling participation.

The wider body of evidence evaluating the association between overall physical activity and type 2 diabetes risk is also consistent the available data on cycling. In 2015, Aune et al. (34)performed a systematic review and meta-analysis of studies investigating the association between physical activity and risk of type 2 diabetes, reporting that participation in 5 h per week of leisure-time physical activity was associated with a 25% lower risk of incident type 2 diabetes than no leisure-time physical activity participation, with the shape of the dose-response curve being curvilinear, such that the largest differences in risk were observed when comparing those undertaking approximately 1–3 h per week of leisure-time physical activity with those undertaking none.

Thus, the available evidence for cycling participation and risk of type 2 diabetes enables broadly similar conclusions to be drawn as the data for cycling and risk of mortality. Cycling is associated with lower risk of type 2 diabetes and substantial differences in risk are seen when comparing individuals who undertake some, compared to those who undertake no regular cycling. Approaches to encourage individuals who currently do not cycle regularly to do some cycling is likely to lead to substantial public health gains.

2.5. Cycling and risk of obesity

Cross-sectional studies generally report that individuals who participate in cycling have a lower body mass index (BMI), and a lower prevalence of overweight and obesity, than their non-cycling counterparts (27, 28, 35–39). Relatively few prospective studies have evaluated the association between participation in cycling and future risk of overweight or obesity or future changes in body weight. These studies are summarised in **Supplementary Table S6**. Taken together these studies suggest that participation in cycling has a modest association on change in weight or BMI (<1 kg difference compared with not cycling), waist circumference (~0.5 cm difference) and incidence of obesity (~15%–25% lower risk of developing obesity) (31, 40–42). This is consistent with analyses of the association of overall physical activity and changes in weight and waist circumference (43). While these differences may be small on an individual level, at a population level they may be sufficient to elicit a public health gain, suggesting that cycling could contribute to public health strategies for obesity prevention.

2.6. Cycling and bone health

Physical activities which are weight-bearing and induce substantial skeletal impacts are associated with benefits on bone health, including higher levels of bone mineral density (44–46) which can potentially lead to lower risk of osteoporosis and fracture particularly in older adults (46–48), but as cycling is non-weight bearing form of physical activity, it is not possible to simply extrapolate evidence from other forms of activity to cycling.

Olmedillas et al. published a systematic review of the evidence on cycling and bone health (49). The majority of included studies were of high-level competitive cyclists, and suggested that cycling at this level does not generally appear to have a beneficial effect on bone mineral density, and may be associated with low bone mass in some cases (49).

One study included in the review reported that sprint cyclists had stronger bones than longer-distance cyclists (50); another reported that cross-country mountain bikers had higher bone mineral density than road cyclists (51), which is consistent with the higher mechanical loading to bone experienced during sprint cycling and mountain biking compared to endurance road cycling.

There is an absence of data in the literature on the effects of participation in transport and recreational cycling on aspects of bone health. Such studies are needed but given that high level competitive cycling is associated with neutral or negative effects on bone health, it seems unlikely that recreational or transport cycling would have a substantial positive effect in this domain. Thus, particularly for people at risk of osteoporosis (for example women and older adults), the available evidence suggests that cycling should probably not be the sole form of physical activity undertaken and should ideally be supplemented with other forms of bone-strengthening weight-bearing physical activities to maximise bone health. A time-efficient way to do this might be to perform exercises such as vertical jumps (e.g., ~50 jumps per session in sets of 10–20) a few times per week (46).

2.7. Evidence from intervention studies on cycling and health outcomes

A combination of observational and intervention studies is needed to gain a complete picture of how cycling participation affects health outcomes. However, studies evaluating the effects of cycling interventions specifically on health outcomes are limited. In 2011, Oja et al. (52) undertook a systematic review of studies evaluating health benefits of cycling (excluding studies of stationary cycling on a cycle ergometer) and identified four intervention trials (53–56). These studies and other cycling intervention studies evaluating health outcomes of real-world cycling interventions (as opposed to intervention using stationary cycle ergometers) published since publication of this systematic review (57, 58) are described in **Supplementary Table S7**.

The overall picture is that the evidence-base for cycling interventions and health outcomes is very limited, with the published studies all being small (less than 100 participants) and generally short-term. The available evidence indicates that cycling interventions improve cardiorespiratory fitness. There is no clear evidence which indicates effects on body composition or on biomarkers of chronic disease risk, which is likely due to the studies being too small to have sufficient statistical power on these health outcomes. The long-term effects (>1 year) of cycling interventions on *any* health outcomes are also not known at present. Thus, adequately powered larger, longer-term studies are urgently needed to establish the extent to which feasible large-scale cycling interventions are likely to alter health outcomes in real-world settings.

2.8. Summary of evidence on cycling and physical health outcomes

There a large body of observational data indicating an association between participation in cycling and favourable health outcomes, with the evidence suggesting the largest potential public health gains are likely be realised by encouraging individuals who currently do not cycle regularly to do some cycling, rather than getting those who currently cycle regularly to cycle more. The evidence also indicates that the benefits of cycling are broadly similar to other forms of physical activity, thus to maximise gains in public health, it would be important to increase participation in cycling amongst individuals who currently undertake little physical activity, rather than encouraging those who are currently active in other pursuits to switch to cycling. However, the evidence from intervention trials is much more limited. Thus, there is a clear need for longer, larger RCTs to evaluate the size of potential health gains which are realistically achievable from pragmatic real-world interventions to promote cycling. **Table 2** provides a summary of what is known and what is not yet know about cycling and physical health.

3. The benefits of cycling on mental health, quality of life, and wellbeing outcomes

A large body of evidence suggests that physical activity in general is associated with a range of positive mental health and wellbeing outcomes, including increased sleep quality, improved executive function and other components of cognition, reduced risk of depression and depressive symptoms, and higher perceived quality of life (59, 60). However, there is more limited evidence on outdoor cycling specifically and mental health, quality or life and wellbeing outcomes. Key studies on this topic are summarised in **Supplementary Table S8**.

A consistent body of evidence from cross-sectional studies suggests an association between cycling and aspects of mental health, quality or life and wellbeing outcomes. For example, cross-sectional studies have reported associations between cycling and lower levels of perceived stress (61, 62), higher levels of commuting enjoyment (63), better perceived general health (64, 65), high levels of quality of life (66, 67), and higher life satisfaction (68). Evidence from cross-sectional (69) and prospective cohort (70) studies have also indicated that cycle commuters have less sickness absence (by∼1 day per year) compared with those who commute to work by other means.

Intervention trial data are more limited. One non-randomised intervention trial indicated that an intervention increasing commuting cycling led to greater vitality at 6 months, but this was not sustained until 1 year (55). Thus, the available evidence for cycling and health, quality of life and wellbeing outcomes, while relatively limited, is consistent with the evidence base for overall physical activity which indicates benefits for these outcomes.

There is a clear lack of trial data about whether interventions to increase cycling will improve mental health, quality of life and wellbeing. Randomised controlled trials to quantify the effect of pragmatic and feasible cycling interventions on these outcomes are urgently needed. In particular, understanding whether cycling interventions can reduce sickness absence amongst employee could potentially play a key role in encouraging employers to introduce interventions and policies which facilitate active commuting. **Table 2** summarises what we know and what we do not yet know about cycling and mental health, quality of life and wellbeing.

4. The risks of collisions and exposure to air pollution for cyclists

4.1. Cycling and risk of collisions

Collision rates in cycling can be expressed based on a number of different exposure measures, including collisions per trip, per unit distance, or per unit time, amongst others (4). The most appropriate measure will depend on the context—collision risk of cycling in comparison to cars is higher when expressed per unit distance than per unit time or per trip as cars travel much faster and further than cycles for any given trip (4, 71). This has led some cycling advocates to suggest that a distance-based comparison of cycling and car safety is not appropriate unless only short-distance car journeys which could be feasibly replaced by cycling are compared, and long-distance car travel (which is an order of magnitude less dangerous than local driving) is excluded (4, 71).

Figure 2 shows rates of cycling fatalities and injuries for cyclists, expressed per unit distance, from selected countries in 2004 to 2005 taken from a 2008 review by Pucher and Buehler (72). This indicates that absolute rates of injuries are low, and fatalities are very rare events, however these are lowest in countries with high levels of cycling infrastructure.

Mindell et al. (71) reported hospital admissions and mortality data in England in 2007–2009 for cyclists, pedestrians and car/van drivers by age and sex groups, revealing that all-age fatalities varied within the same factor-of-three range for men (0.15–0.45 fatalities per million hours' use) and women (0.09–0.31 fatalities per million hours' use) across these three transport modes, but with substantial variation by age and sex, with a higher fatality risk for driving compared with cycling for young men, and relatively higher risks for cycling mortality in men aged over 70 years. Risks of hospital admission from cycling (29 admissions per million hours' use in men and 28 admissions per million hours' use in women) were higher than for driving (1.6 admissions per million hours' use in men and 1.8 admissions per million hours' use in women), but for cycling this does include admissions due to activities such as mountain biking and BMX, as well as cycling for transport, so does not provide a true like-for-like comparison with driving (71).

Risks of cycling vary according to route infrastructure with lower probabilities for a crash being evident on protected bike lanes (by ∼30%–90%) than on roads shared with motorised traffic (73, 74). A review by Reynolds et al. concluded that clearly marked bike-specific facilities were consistently shown to improve safety for cyclists, reducing injury or crash rates by about half compared to unmodified roads (75).

Overall, absolute risk of collisions with cycling are somewhat higher than driving, but still very low in absolute terms, and the health benefits of cycling are more than 21 times greater than any increased risk of collision (76). In short, even with current levels of cycling collision rates, the benefits of cycling substantially outweigh any increased collision risk. However, there is clear potential to reduce the collision risk associated with cycling further. Risks of cycling are lower in countries with good cycling infrastructure (71, 72, 77), and there is clear evidence that

TABLE 2 What is known and what is not yet know about the benefits and risks of cycling.

	What is known	What is not yet known	What is needed to fill evidence gap
Cycling and physical health outcomes	• A large body of data from prospective cohort studies indicates that participation in cycling is associated with lower risk of mortality from any cause, cardiovascular disease and type 2 diabetes. • The dose-response relationship is curvilinear with the largest lowering of risks seen when comparing no cycling with moderate levels of cycling. Thus, the largest potential for health gains likely to come from increasing participation amongst those who do not currently cycling regularly, rather than encouraging those who already cycle regularly to cycle more. • Evidence from prospective cohort studies for an association of cycling participation and cancer incidence and mortality is more mixed, with one major study showing lower cancer risk amongst regular cyclists, but other studies showing no significant association. This may reflect, in part, insufficient statistical power to detect any such associations. • In prospective cohort studies, there is evidence of a modest association between cycling participation and lower bodyweight (<1 kg difference compared with not cycling) and waist circumference (by ∼0.5 cm). These differences are relatively small on an individual level but may at a population level be sufficient to elicit a public health gain. • The association between cycling and bone health appears to be neutral at best, and may be negative for high level competitive cycling. Thus, particularly for people at risk of osteoporosis (for example women and older adults), the available evidence suggests that cycling should probably not be the sole form of physical activity undertaken, and should ideally be supplemented with other forms of bone-strengthening weight-bearing physical activities to maximise bone health. Evidence from a small number of intervention trials indicates that increasing cycle commuting leads to improvements in cardiovascular fitness, but effects on body weight or on biomarkers of chronic disease risk are unclear.	• The observational nature of the majority of the available data makes difficult to draw firm conclusions about the extent to which the associations between cycling and health outcomes are causal, or the extent to which pragmatic, real-world interventions to increase cycling are likely to induce a sustained impact on health outcomes (or biomarkers of risk for such health outcomes). • Effects of cycling interventions on health outcomes other than cardiorespiratory fitness are currently unclear, as studies have generally been small, short-term, with insufficient statistical power to detect such effects.	• Large-scale, long-term (at least 1 year duration, ideally longer) interventions trials (ideally randomised) are needed to evaluate the sustained effects of increasing cycling participation amongst those who don't currently cycle regularly on health biomarkers causally related to risk of chronic disease (for example, adiposity, blood pressure, blood lipids, glucose, insulin). • Such trials would ideally encompass a wide range of demographic groups. • Such trials will provide evidence of a causal relationship between cycling participation and health outcomes and enable quantification of the extent to which health outcomes can be realistically altered by increasing cycling participation. This is vital evidence for public health decision makers.
Cycling and mental health, quality of life and wellbeing	• In cross-sectional studies, participation in cycling is associated with lower levels of perceived stress, higher levels of commuting enjoyment, better perceived general health and higher perceived quality of life. This is consistent with the wider evidence base on physical activity in general and mental health, quality of life and wellbeing outcomes. • Cross-sectional and prospective cohort studies suggest that cycle commuting is associated with less sickness absence amongst employees	• It is not known whether associations between cycling and favourable mental health, quality of life and wellbeing are causal. From the available evidence it is not possible to fully exclude the possibility that those with better perceived health or quality of life may be those who choose to cycle more, rather than cycling leading to improvements in these health outcomes. • It is not known the extent to which pragmatic, large-scale interventions to increase cycling amongst those who do not cycle regularly can produce sustained improvements in mental health, quality of life and wellbeing outcomes.	• Intervention trials (ideally randomised) are needed to evaluate the effects of increasing cycling participation amongst those who don't currently cycle regularly on these outcomes. • Such trials would ideally be large, encompass a wide range of demographic groups, and long enough to evaluate sustained effects (ideally at least 12 months). These trials will also enable quantification of the extent to which these outcomes can be altered by increasing cycling participation.
Risks of cycling associated with collisions and exposure to air pollution	Collisions • Risks of collisions with cycling are somewhat higher than driving, but still very low in absolute terms	• Collision risks of cycling compared with driving when true like-for-like comparisons are made (for example excluding motorway driving, and off-road cycling such as mountain biking and BMX)	• Further studies making better like-for-like comparisons of collisions associated with cycling and other modes of transport • Studies examining the risks of cycling at different levels of air pollution in populations

(*Continued*)

TABLE 2 Continued

	What is known	What is not yet known	What is needed to fill evidence gap
	• The health benefits of cycling are more than 25 times greater than the slightly increased risk of collision risk • Collision risks are lower where there is good cycling infrastructure and providing physical separation between bicycles and motor vehicles improves safety Air pollution • Higher ventilation rates during cycling mean inhalation of air pollution particles can be higher during cycling than driving, but pollution gradients are steep on and near roadways so small changes in position on the road relative to vehicles can have substantial effects on exposure • Using cycle lanes and lower traffic routes can reduce exposure to air pollution for cyclists • The health benefits of cycling substantially outweigh the potential risks of increased exposure to air pollution in all but the most extreme air pollution conditions worldwide. Even in Delhi (the most polluted city on the WHO database) undertaking up to 45 min of cycling per day was estimated to provide a net health benefit.	• Risks of cycling in polluted environments for susceptible populations, for example those with respiratory problems are uncertain • Limitations in modelling risks associated with pollution, for example by only considering long-term average exposure levels, add uncertainty to the risk estimates	who may be more susceptible to adverse consequences of high levels of air pollution • More sophisticated studies modelling the impact of pollution exposure during cycling on health outcomes, taking into consideration varying exposures to air pollution

Economic benefits and costs of cycling	• Replacing car journeys with cycling journeys is likely to be cost saving to the individual. Limited data suggest that overall cost per km travelled, taking into account direct financial outlays, costs of time, health benefits and risks of collisions for cycling is less than half that for car journeys.
	• Limited data suggests that increasing cycling amongst employees is likely to be cost saving to employers in terms of lower absenteeism costs.
	• Cycling generate has the potential to substantial economic benefits to related to health. For example, economic modelling studies have projected that:
	  ◦ Increasing cycling to 25% of all journeys in the UK by 2050 would provide over £42 billion in economic benefit (including £35.5 billion due to personal health gains).
	  ◦ Increasing cycling by 3 km per day and walking by 1 km amongst individuals in urban centres in England and Wales would result in £17 billion in savings to the NHS over 20 years
	• Replacing car journeys with cycling would result in economic benefits in terms of lower pollution and emissions
	• Losses related to reduced duty and taxation associated with replacing car journeys with cycling are more than an order of magnitude lower than the benefits. It may be cost effective to society to subsidise cycling to increase uptake.
	• In 2011, cycling contributed an estimated £2.9 billion to the UK economy
	• Investing in cycling infrastructure creates more jobs than the same level of investment for other transport infrastructure
		• Economic models of cost-benefit of replacing car journeys with cycling for the individual have only been undertaken in limited settings, and do not currently include key aspects such as personal valuation of safety, potential discomfort and other costs such as insurance.
		• Estimates of absenteeism cost savings to employers associated with cycling amongst employees are based on observational estimates in a limited range of occupations, and the extent to which interventions to increase cycling participation would change absenteeism rates are not known. The effects of cycling amongst employees on productivity outcomes other than absenteeism is also not known.
		• RCTs which capture the full cost savings to an individual (and employer) and their value of time have not been conducted. This would inform the most worthwhile investment of new cycling initiatives.
		• Methodologies such a cost-benefit analyses, conducted from a societal perspective are challenging to conduct and to date few have been fully societal in their assessment of benefits.
		• From a behavioural economics perspective, we don't know which attributes predict changes in cycling behaviour of the adult population and what the trade-offs are. For example, are people willing to commute for a longer time to increase their personal health benefits? Are people willing to accept financial incentives to increase their cycling level? Is there a gender balance effect on cycling levels and if so, what do women/men need to incentivise them to increase cycling activity?
			• Large-scale, long-term interventions which capture all resource use and costs relating to an individual's cycling behaviours and their health-state would facilitate a more accurate understanding of costs and possible associated benefits.
			• Societal cost-benefit analyses detailing the costs and benefits across multiple sectors such as health care, employment, transport, retail and education would generate the full societal picture of increasing cycling.
			• Evidence is needed on the attributes (and levels) which predict cycling uptake for women and men along with evidence on the trade-offs between attributes such that initiatives can be optimally designed tailed to increase cycling.

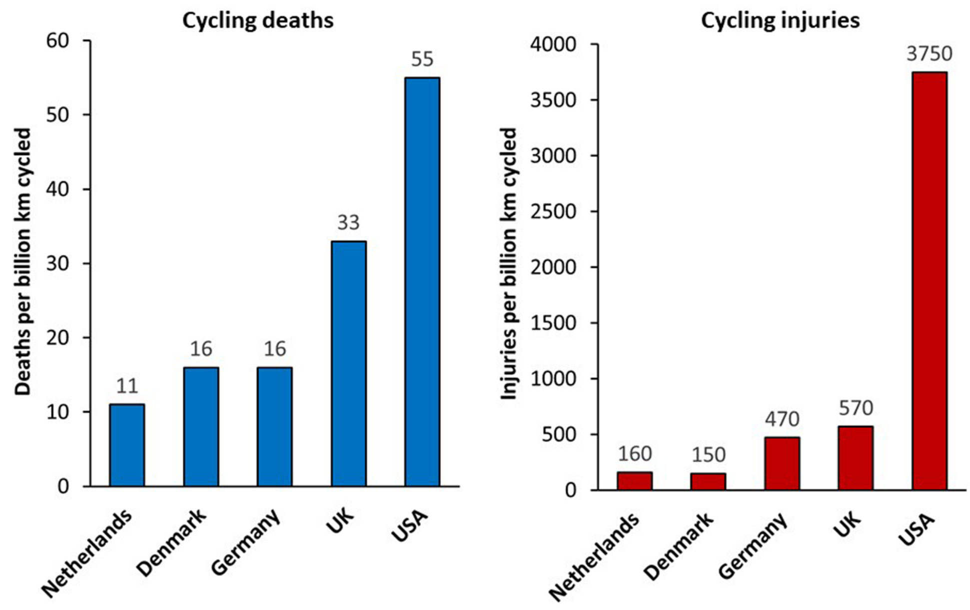

FIGURE 2
Rates of cycling deaths and non-fatal injuries in selected countries in 2004–2005. From (72).

improving cycling infrastructure and providing physical separation between bicycles and motor vehicles improves safety (78).

Modelling the impact of interventions on cycling collision risks is complex and findings are difficult to generalise, but the available evidence indicates that increases in cycling lead to disproportionately smaller increases in collisions and that the negative impact of collisions do not outweigh the benefits of physical activity from cycling (78, 79).

4.2. Cycling and risk of exposure to air pollution

This section considers the risks of exposure to air pollution to the individual cyclist while they are cycling. Exposure to air pollution tends to be higher when travelling on roads than during most other activities due to proximity to motor vehicles (80). This is particularly in urban environments with high vehicle density, during peak commuting hours and exposure to pollution during commuting makes a substantial contribution to total personal exposure to air pollutants (81).

Karanasiou et al. (81) undertook a review of levels of personal exposure to key air pollutants during different modes of commuting. Twenty European studies were identified which calculated exposure to air pollution during cycling, which reported exposures for PM2.5 in the range 29–72 μg/m^3, P10 in the range 37–62 μg/m^3, black carbon in range 3–21 μg/m^3 (81). These exposure levels were broadly similar to those in cars (P2.5 22–85 μg/m^3, P10 36–76 μg/m^3, black carbon 6–30 μg/m^3) (81). When the higher ventilation rates, and potentially longer travel times, for cyclists are taken into account, inhaled doses of particles can be up to 4–7 times higher than car passengers on the same route (80, 81).

A key issue is whether adverse effects of exposure to pollution negates health benefits of cycling when cycling in areas with elevated levels of air pollution. The available evidence suggests that this is not the case. In a prospective cohort study of over 52,000 Danish adults aged 50–65 years, followed up for 13 years, reductions in risk of disease specific (cardiovascular disease, respiratory disease, diabetes) and all-cause mortality associated with cycling were not modified by level of exposure to traffic-related air pollution (assessed as NO_2) exposure (22).

Modelling studies of the effects of cycling on health outcomes also estimate that the health benefits associated with increased physical activity from cycling are several fold higher than the risks associated with increased inhaled air pollution doses. Mueller et al. (82) reported that health impacts related to differences in air pollution exposure were small, and the benefits associated with increased physical activity associated with taking up cycling were appromately an order of magnitude greater than the risks to the cyclist assocated with increased inhaled air pollution.

Tainio et al. (83), extended this work by modelling the risk-benefit balance of cycling in environments with increasingly high levels of air pollution. In this analysis they calculated a "tipping point" for different levels of air pollution where maximal health benefits are achieved and increasing cycling beyond this level would not accrue further health benefits, and a "breakeven point" where cycling beyond this level would lead to the risks exceeding the benefits. For cities with average the global average level of urban background pollution in the World Health Organisation database (PM2.5 levels of 22 μg/m^3; for context the level in London is lower than this at 16 μg/m^3), the tipping point would only be reached after 7 h per day of cycling and breakeven point would never be reached. For the average European city the tipping point was 2.5 h per day of cycling and breakeven point was 9.25 h of cycling. Even in the most polluted city in the database (Delhi, background PM2.5 levels of 153 μg/m^3) the tipping point was 30 min of cycling per day and breakeven point was 45 min of cycling per day. Thus, the evidence indicates that in almost all but the most extreme air pollution conditions worldwide, the benefits of cycling exceed the risks of increased exposure to inhaled air pollution for all reasonable durations of daily cycling.

A summary of what we know and is not yet know about cycling and risk of collisions and exposure to air pollution is shown in **Table 2**.

5. The economic benefits and costs of cycling

The following section discusses the available evidence and current research gaps on the economic benefits and costs associated with cycling, considering costs to the individual, employers and wider society. We searched the academic and grey literature for reports on the economic benefits and costs of cycling, prioritising reporting data from reviews summarising existing evidence, but also reporting data from individual studies. Thus, this section provides a representative overview of the existing evidence, but does not represent a systematic review of the topic.

When evaluating the economic costs and benefits of cycling (in comparison to other modes of transport), it is important to consider costs at multiple levels. These include costs and benefits:

- To the individual (such as value of time, cost of purchase and depreciation, cost of fuel, health).
- To employers (such as productivity, absenteeism).
- To wider society (such as health and social care, congestion, environmental impact, collisions, taxation, employment).

Costs and benefits of cycling at these three levels are described in the sections below.

5.1. Economic benefits and costs of cycling to the individual

Evidence from Denmark indicates that choosing to cycle over driving a car is cost saving to the individual (84). Taking into account costs from vehicle taxes, fuel, oil, tires, repairs and depreciation, it was estimated that cycling one kilometre costs the individual €0.048 (£0.043), whereas travelling the same distance by car would cost €0.34 (£0.29) (at 2008 prices, currency exchange rates correct as of 06/12/2022 from www.xe.com). If taxation costs (which can vary considerably by country and vehicle emissions) are excluded, the cost of travel was per km €0.039/km (£0.035) by cycle and €0.16 (£0.14) by car.

As cycling is generally slower than driving—although this is not necessarily the case for urban commutes—cost of time is the highest cycling-related cost. Time costs valuations are derived from estimates of a population's willingness to pay for time changes in length of travel time and differ according to mode of transport (car, cycling or public transport)(84). It also differs between societies, so care must be taken in extrapolating Danish time cost data elsewhere. The Danish study assumed cycling speeds of 16 $km.h^{-1}$ and driving speeds of 50 $km.h^{-1}$, and costed driving time at €15.19/hour and €22.86/hour for delays (people as less tolerant of time in traffic, so time is costed higher for delays) and costing cycling time at €12.10/hour and €18.28/hour for delays, equating to a time cost of €0.672/km for cycling and €0.215/km (84).

The Danish reports estimated that cost to the individual of cycling collisions at €0.034/km (vs. €0/km for driving, though driving collisions did incur social costs, see Section **6.3** below), but that cycling was associated with individual gains in terms of prolonged life (by €0.358/km) and improved health (by €0.149/km) (84). Taken all of these factors into account the cost to the individual was €0.243/km for cycling and €0.511/km for travelling by car (84). Thus, overall these data suggest that travelling by cycling, even after accounting for additional time taken, reduces the economic costs of commuting by more than half, but further such economic evaluations in other contexts are needed extrapolate findings beyond a Danish setting. For example, in many urban contexts in the UK, assuming a driving speed of 50 $km.h^{-1}$ is optimistic. Furthermore costs associated with insurance, as well as costs associated with the personal valuation of perceptions of safely (which may increase cycling costs) and potential discomfort during travel were not considered in this economic model. Inclusion of such factors is needed to provide a more complete picture of economic costs and benefits to the individual.

5.2. Cycle commuting and productivity

There is limited evidence available on the effects of cycle commuting on productivity. Data from studies in the UK and Denmark both reported that regular cyclists are more likely to have lower absenteeism per year than their non-cycling counterparts, by approximately 1 day per year (69, 70). A 2007 report by SQW for Cycling England on valuing the benefits of cycling, assumed that increased physical activity from cycling would lead to 0.4 days less absence per year, resulting in £64.40 saving per working person per year [assuming gross value added (GVA) per employee of £37,000 per year] (85).

Data on the cost-benefit of work-based cycle schemes is also limited. A 2008 report from Transport for London summarising the current state of knowledge on cycling in London to inform cycling policy, which reviewed evidence from over 100 studies, identified a work-based cycle pool scheme called Bikes for Business which could reportedly provide savings of £25–80/month per bike to the employer (due to reduced taxi and public transport costs) and approximately £50/month to the individual employee due to reduced travel costs (86). Furthermore, qualitative research reported that this scheme reduced employee travel time and avoided parking problems and was viewed by some employees as directly improving their productivity.

Thus, while the available data on cycling and productivity are limited the current evidence suggests a potential net benefit to employers of higher levels of cycling amongst employees. Development of employer-led interventions to increase levels of cycling amongst employees could conceivably result in net economic benefit to employers, even when costs of the intervention are taken into consideration.

Further research is needed to more robustly quantify the benefits and costs to employers, as well as employees, of pragmatic, large-scale interventions to increase cycling amongst employees. The first stage in this process would be to gain a better understanding of which type of interventions are most likely to be cost-effective in incentivising employees to increase their cycling participation.

5.3. The economic benefits and costs of cycling to wider society

There is a growing body of evidence indicating a net benefit to society of increasing participation in cycling as summarized in the following sections relating to cycling impacts on health, pollution and congestion, duty and taxation and employment and retail.

5.3.1. Economic costs and benefits of cycling in relation to health

To assess the economic costs and benefits of cycling in relation to health, it is necessary to first obtain an estimate of the epidemiological dose-response relationships between cycling and health benefits and health risks, such as pollution exposure and collisions, as well as potential changes to pollution as a result of changes in cycling and then scale them into an impact model according to level or change in level of population cycling (4). These health effects can be expressed in a number of ways. Typically, economists use incidences of chronic diseases prevented, disability adjusted life years (DALYS), premature mortality, years of life lost, or years of healthy life lost), and by placing an economic value on these health outcomes (for example, £30,000 per DALY avoided).

Commonly used models relevant to this report include the World Health Organization's Health Economic Assessment Tool (HEAT) for cycling and walking (87, 88) and the Integrated Transport and Health Impact Modelling Tool (ITHIM) (89). All such models assume that any cycling represents additional physical activity, rather than displacing other forms of physical activity, and also make assumptions about the nature of the dose-response relationship between cycling and health which are not fully understood, for example about benefits of very short duration bike rides and the tradeoff between intensity and duration for benefits (4). Some models attempt to take into consideration differential benefits according to other factors such as age. The models also assume that the epidemiological association between cycling and health outcomes is entirely causal and the level of risk reductions seen with increasing levels of cycling in observational studies would be replicated by interventions to increase cycling, which may not necessarily be the case. Notwithstanding these limitations, several studies have been undertaken to estimate the economic value of potential effects of cycling on health. These consistently report net health benefits of cycling would result in cost savings to national health budgets.

In 2008, Cavill et al. systematically reviewed economic analyses of transport infrastructure and policies which included health effects related to cycling (90). This review, which pre-dated the introduction of the HEAT and ITHIM modelling tools, included 15 studies, 10 of which considered only cycling and five considered cycling and walking, all but one of these studies (which was from the USA) were conducted in European countries. Three studies were considered high quality, five moderate quality and seven low quality in terms of methodology. While the studies were heterogeneous in nature and presented a wide range of results, benefit-cost ratios (present value of benefits/present value of costs) and the value attributed to each new cyclist were frequently reported outcomes. All but one study reported a positive benefit-cost ratio, with a median benefit-cost ratio of 5:1 and a range from −0.4 to 32.5. However, the authors suggested that these values should be treated with caution given the different assumptions made across studies. Six studies presented results in terms of value attributed to each new cyclist ranging from €127 to €1,290, with much of the difference in value due to different assumptions [some which Cavill et al. (90) considered incorrect], and many studies not being transparent in their methods. However, these values are in line with a report by SQW Consulting for Cycling for England which estimated the monetary value of one additional cyclist cycling for one year, replacing 50% of car trips with cycling trips. These models calculated benefits of £408.67 per cyclist per year in terms of lower risk of loss of life with an additional £28.30 per year in NHS savings (91).

Some reports have attempted to quantify population-level health cost savings associated increasing levels of cycling, or active travel. Jarrett et al. (92) modelled the effects on NHS costs (including management and treatment of acute and chronic diseases, and road traffic injuries) over 20 years of increasing cycling by 3 km per day and walking by 1 km per day, amongst all individuals in England and Wales living in urban areas (those with 20,000 residents or more). The model estimated a saving of ~£17 billion over 20 years to the NHS budget (at 2,010 prices)—approximately 1% of the yearly health care budget.

A report by Fishman and coworkers (93), used HEAT to estimate the economic health benefits of cycling in the Dutch population. Based on age-specific weekly cycling times (average of 74 min per week across the age range from 20 to 90 years) and mortality rates it was estimated that current levels of cycling prevented 6,657 deaths per year in the Netherlands, resulting in a 0.57 year increase in life expectancy and an annual economic benefit of €18.6 billion, assuming a value of a statistical life of €2.8 million per prevented death.

5.3.2. Economic benefits and costs of cycling in relation to pollution and congestion

The available evidence, albeit limited, quantifying the benefits of cycling on congestion and pollution consistently reports that increased cycling levels would lead to reductions in associated costs. These approaches model the effects of replacing car journeys with cycling journeys and monetary attribute costs to reductions in emissions, noise and congestion. Using this approach it was estimated that, in Copenhagen, replacing car travel by cycling would result in a saving of €0.004/km in air pollution costs, €0.005/km in climate change costs, €0.0062/km in congestion costs (84, 94).

Crawford and Lovelace (95) used Transport Analysis Guidance (TAG) data from the Department for Transport to estimate pollution and congestion cost savings which could be realised by meeting CDP and GBC cycling targets in 2025 and 2050. Compared with a baseline of zero growth in cycling:

- The CDP plan was projected to result economic benefits in 2025 of £283.5 million in reduced congestion, £10.9 million in reduced greenhouse gas emissions, £2.4 million in decreased noise and £1.5 million in improved air quality. Corresponding economic benefits in 2050 were £956.3 million (reduced congestion), £36.6 million (greenhouse gases), £7.9 million (noise) and £5.2 million (air quality).
- The more ambitious GBC target was projected to result in economic benefits for congestion, greenhouse gases, noise, and air quality of £1.09 billion, £41.5 million, £9.1 million, and £5.9 million, respectively in 2025; and £7.1 billion, £271.6 million, £59.2 million, and £38.6 million, respectively in 2050.

Modelling studies evaluating potential effects of increasing levels of cycling for transport on air pollution (**Table 2**) also considered the effects on costs associated with congestion. Creutzig and coworkers (96) modelled the effects of policy scenarios to reduce motorised transport use and increase use of public transport and non-motorized transport, which including increasing cycling infrastructure, on pollution and congestion in four European cities. Economic values for pollution changes were not reported, but it was estimated that transport scenarios in Malmo and Freiburg which resulted in increases in non-motorised transport trips by ∼50% would provide estimated economic benefits of reduced congestion of €363 million per annum (∼€800 per person per annum) and €184 million per annum (∼€650 per person per annum) respectively in the two cities.

6. The barriers to cycling participation

A detailed understanding of barriers to cycling amongst those who do not cycle regularly is essential to inform the design of effective interventions to facilitate increased levels of cycling. This section discusses the evidence on barriers to increasing cycling in adults. This evidence comes from two sources. First, peer-reviewed studies were identified via searches of key databases [PubMed, CINAHL (Cumulative Index to Nursing and Allied Health), AMED (Allied and Complimentary medicine database), PeDRO (Physiotherapy Evidence Database), Cochrane library]. Although our search was not exhaustive, it is likely that the evidence presented here is representative of the evidence base. There were 10 studies identified; these included one systematic review (97) and nine further original research studies (98–106) which employed a range of quantitative and qualitative methods, including surveys, interviews and focus groups (**Supplementary Table S9**).

6.1. Environmental barriers to cycling

The systematic review, which included 21 observational studies from five countries (14 from the USA, three from Australia, two from the UK, and one each from Canada and the Netherlands) focused on the effect of the environment on cycling levels (97). It reported that key environmental-level barriers to cycling included: perceived and objective traffic danger; distance from cycle paths; long trip distance and steep inclines, leading to; and high levels of effort.

Conversely, the presence of dedicated cycle routes or paths, separation of cycling from other traffic, high population density, short trip distance, and proximity of a cycle path or green space were positively associated with cycling (97). Similar environmental-level barriers to cycling were also reported by studies not included in the review. The main findings from these additional studies were that the main barriers to cycling were: low perceived safety (98–100, 102, 103); lack of cycling infrastructure (including secure cycle parking and shower facilities) (98–103); distance and perceived effort (100, 102, 106); and bad weather (98–100, 104, 106).

Related to safety, three studies further identified the perceived poor attitude of other road users as a barrier to cycling (98, 102, 103). They recommended education for other road users on safe interaction with cyclists, and the promotion of cycling as a mode of transport (not just a recreational activity) to help normalise it within a population.

One study reported that owning a car was negatively associated with using a bike as a mode of transport (101), and suggested making it less appealing to use a car (e.g., raising the cost of parking at work) may help to increase cycling amongst car owners.

One study used a modelling approach to predict that increases in numbers of people cycling would lead to greater political will to improve the cycling environment and a "safely in numbers" effect that would increase the perceived and actual safety of cycling, thereby creating a virtuous cycle for growth (103).

Finally, at an environmental level, the presence of dedicated cycle routes or paths, separation of cycling from other traffic, high population density, short trip distance, and proximity of a cycle path or green space appear to be positively associated with cycling (97).

6.2. Individual-level barriers to cycling

The studies that were not included in the review also reported on individual-level, barriers to cycling. These included: lack of skills and confidence (100, 101, 105); physical discomfort and impracticality of cycling (104–106); and cost (99), although cost-saving was also reported as a facilitator to cycling (98, 99).

In contrast to studies undertaken in areas with relatively weak infrastructure (98–103), in countries where cycling infrastructure was good (Netherlands, Belgium), individual-level factors were generally more important than environmental-level factors in predicting cycling behaviour (105, 106). While the relative importance of individual vs. environmental barriers will be context-specific, this evidence suggests that focusing solely on improving infrastructure may not be sufficient to maximise cycling participation.

Connell et al. conducted a full exploration of barriers for office workers for the development and optimisation of a workplace cycling intervention (107). They first nationally representative survey of UK adults, then undertook focus groups with bank employees to understand any context-specific barriers and ways in which these might be overcome. These activities led to identification of 10 individual-level, two social-level, and five organizational-level modifiable factors, which were mapped to candidate intervention components previously identified in a scoping review of cycling initiatives (5) This work led to the development of a tailored multi-component workplace cycling intervention designed to address as many barriers to cycling to enable a sustained uptake in cycling behaviour in bank employees.

There were a number of evidence gaps in the peer-reviewed literature, particularly on barriers to cycling in older adults and disabled populations. Most studies specifically examined cycling as a mode of transport (99–102, 105, 106) or explored barriers to transport and recreational cycling combined (97, 98, 103, 104). Information on perceived barriers to recreational cycling specifically (which are likely to differ from barriers to cycling for transport) was limited.

6.3. Summary of evidence on barriers to cycling

The main barriers to cycling operate on both environmental (lack of facilities and infrastructure, weather, and perceived effort due to long distances, hills) and individual [perceived lack of safety and lack of confidence, skills and time, and perceived inconvenience/impracticality relative to alternatives (i.e., using the car)] levels.

Importantly, women may be more concerned about safety and lack confidence to a greater degree than men, and even where cycling infrastructure is good, individual barriers remain important.

In addition, the promotion of cycling as an everyday (useful, enjoyable and social) activity, rather than a sport will be needed to maximise uptake of cycling. A multi-faceted approach targeting different population groups in different contexts is therefore needed to reduce barriers to cycling and facilitate increased participation.

However, more research is needed to understand specific barriers to recreational cycling, and in different population groups (i.e., older people, specific disabilities, specific BAME groups). **Table 1** summarises what we know and what is not yet know about barriers to cycling.

7. Potential solutions to increase the number of people cycling: what has worked, what hasn't worked, and what could be tried?

When implementing and evaluating potential solutions to increase the number of people cycling, it can be helpful to think about the "level" of the intervention. A useful and previously used (108) model is the social-ecological framework (109). The factors that can influence a behaviour (in this case cycling) and also the levels at which interventions and actions can be aimed at: the *individual* level (may include biological and psychological approaches); the *social* level (may include family, group, cultural and community approaches); interventions at the *physical environment* level (could include facilities and infrastructure); and the *policy* level (may include legislation, funding and national strategies and priorities).

7.1. The current evidence for the promotion of cycling

The evidence for the promotion of cycling draws from different study types; observational studies examining factors which influence cycling; experimental studies, empirical studies such as natural experiments, and evaluations of public health policies. In the past two decades there have been numerous attempts to synthesise this evidence. **Table 3** provides an overview of the current evidence base for the promotion of cycling using key selected systematic reviews and public health guidance reports.

There are many potential solutions to increase cycling which exist across all four levels of the socio-ecological model and which may target different types of cycling. For example, interventions have attempted to increase commuter cycling at the level of the *individual* (123), longitudinal studies (observing people over time) provide evidence of how changes in the *physical environment* may lead to changes in leisure and/or transport cycling (111), and policies have been developed to promote active travel to impact at community, city and population levels (112).

Not all reviews in **Table 3** report consistent findings in the expected direction for a particular intervention or action. This may be attributed to differences in: the aim of each review; the types of study included within each review; and the methodological quality of individual studies with a review.

It is also important to consider that some potential solutions may only have an impact on one type of cycling; as an example, the provision of new cycle paths in a city centre may lead to an increase in cycling for transport but have no effect on cycling for recreation, or vice versa. Additionally, when designing and evaluating interventions and policies to increase active transport cycling is often combined with walking; this can make it difficult to identify what actions are specifically targeted towards cycling and what the impact of the intervention is on cycling.

There are clearly some challenges to identifying the optimal solutions to promote cycling from the existing evidence base. However, acknowledging these challenges, it is possible to identify a range of promising and potential solutions from across the different levels of the socio-ecological model.

7.1.1. The individual level

The evidence base is relatively small and inconsistent at this level. Several studies implemented walking and cycling actions in the form of *self-help materials* and *targeted behaviour change programmes* for

TABLE 3 An overview of key reviews on potential solutions and facilitators for promoting cycling.

Author	Level of intervention in the social-ecological model	Main findings
Kelly (5)	Individual Social	A scoping review of literature on individual, social, and organizational level interventions to improve cycling levels. The study creates a map to summarise the broad action types (described by Michie et al. 110) feasible for implementation within organization/group-based cycling promotion initiatives, to act as a critical tool for employers, communities, practitioners, and researchers in designing interventions to increase cycling.
Kärmeniemi (111)	Physical environment	A systematic review of before-and-after design studies to assess how impacting the built environment impacts on physical activity. New routes and bike lanes, traffic free routes, perceived access to destinations, bus-ways with parallel cycling paths, and reductions in perceived danger all predicted increases in cycling.
Winters (112)	Policy	Found evidence that policies related to active travel may operate at various levels of the socio-ecological framework, including society, cities, routes or individuals. The provision of convenient, safe and connected walking and cycling infrastructure is at the core of promoting active travel, but policies may work best when implemented in comprehensive packages.
Savan (113)	Social Individual	Based on a comprehensive literature review, key elements from the social psychology literature associated with successful cycling adoption initiatives were reported. Five key interlocking strategies were described: (1) strategic population segmentation; (2) identification and removal of barriers; (3) the use of commitment strategies, including the foot in the door and pledge techniques; (4) tactics to sustain behaviour change, including visual images, prompts, reminders, social cues and modelling, social norms, branding, feedback and incentives, and; (5) ongoing social support, through modelling, local hubs and community involvement.
Giles-Corti (114)	Physical environment Policy	This narrative review identified eight integrated interventions that are needed to create cities that promote (walking and) cycling. "Urban" and "Transport planning and design" policies were differentiated. Planning interventions included destination accessibility, employment distribution, and parking demand management. Urban design interventions included connective design, residential density, distance to public transport, land-use diversity, and neighbourhood desirability.
Fell and Kivinen (115)	Social Physical environment	This review reported that there is a widespread agreement in the literature that the most effective mechanisms for boosting cycling (and walking) comprise integrated and complementary packages of interventions. Infrastructure is generally regarded as necessary but not sufficient to boost cycling and walking; while behaviour change interventions in the absence of adequate enabling infrastructure are also judged unlikely to be effective. Effective interventions include; Personal travel planning, Cycle to Work days, Cycle-hire/bike-share schemes, Provision of dedicated cycling lanes (and bicycle parking) and Some school-based interventions. The best investment strategy may comprise a strategic, networked approach and is likely to comprise a mix of measures.
Stewart (116)	Social Physical environment	A systematic review of 12 studies which aimed to increase commuter cycling. Group level approaches: Three bike to work schemes had mixed, but generally positive effects. A self-help programme did not impact cycling, but a support programme that provided social support and bicycles had a large effect. A 2 month cycling training programme had no effect, while a 12 month programme did. Environmental approaches: A single infrastructure project (building a bridge) increased cycle commuting, while two city-wide infrastructure interventions had positive impacts. Two whole of city investment approaches had small positive effects that were considered difficult to detect.
Hunter (117)	Social Physical environment	A systematic review of 12 studies to promote physical activity in urban green space. An urban greenway trail designed to enhance connectivity of pedestrian infrastructure with nearby retail establishments and schools, showed increases in cycling. A promotion campaign of a newly constructed Rail Trail that included press ads, maps of trails, newspapers and local radio, brochures distributed to local organizations and schools, and a launch event showed that intervention group cyclists increased mean cycling time compared to control area cyclists, and mean bike counts on the trail increased after the trail launch.
Mayne (118)	Physical environment	A systematic review of natural or quasi-experiments to examine the effects of policy and built environment changes on obesity-related outcomes; 17 addressed physical activity. Bike lanes and off-street bike paths increased cycling in three out of four studies. Two studies found increased cycling after implementation of the London and Montreal bicycle share programmes.
Community Preventive Services Task Force (119)	Physical environment	A systematic review of 90 studies provided evidence for the effectiveness of cycling infrastructure including protected bicycle lanes, trails, traffic calming, intersection design, street lighting and landscaping.
Scheepers (120)	Individual Social Physical environment	This review reported interventions categorised as work-place, changes to urban design, population-wide, and bike sharing which were typically multi-component, including self-help materials, public awareness, social marketing campaigns, and workplace travel plans. Of 14 studies which reported effects on cycling, 10 reported increases in cycling. Increases in cycling were reported for an annual short term campaign, workplace travel plans (e.g. storage, subsidized bicycles, facilities), commuter cycling promotion, financial incentives, car-free city centres, town-wide initiatives, cycle proficiency classes, individualised marketing, smart bicycles, and bicycle sharing schemes. Negligible effects for neighbourhood trails, traffic tolls, national cycle networks, cycle paths.

(*Continued*)

TABLE 3 Continued

Author	Level of intervention in the social-ecological model	Main findings
Bird (121)	Individual	A systematic review investigated what individual level behaviour change techniques have been used to promote walking and cycling. Of 46 included studies, $n = 16$ reported combined walking and cycling findings (none were cycling only). While the findings were mixed, they generally supported the inclusion of self-monitoring and intention formation techniques in future walking and cycling intervention design.
National Institute for Health and Care Excellence (122)	Individual Social Physical Environment Policy	Guidance on how to increase (walking and) cycling. Policy and planning recommendations included ensuring high-level support from the health sector and ensuring all relevant policies and plans consider (walking and) cycling. Local action recommendations included developing programmes, community wide-programmes, and personalised travel planning. A focus on schools, workplaces and the NHS was also recommended. Other measures to tackle the wider influences on walking or cycling were recommended including measures to reduce road dangers and to reallocate road space to create a more supportive environment. The need to address health inequalities around (walking and) cycling was emphasised.
Fraser (97)	Physical environment	This review reported evidence from observational studies examining associations between cycling and the built environment. Positive associations were identified between cycling and dedicated cycle lanes and 'safe routes to school programme'.
Yang (123)	Individual Social	A systematic review of actions to promote cycling. Promoting specifically cycling: an intensive individual intervention in obese women, high quality improvements to a cycle route network, and two multifaceted cycle promotion initiatives at town or city level were found to be associated with increases in cycling. An educational and promotional intervention for cycling to school did not impact school journeys but increased recreational cycling. A community based social marketing programme involving information provision, cycle training, free bike hire, and a Ride To Work Day campaign aimed to promote the use of existing cycle paths showed residents no overall increase cycling. Individualised marketing of "environmentally friendly" modes of transport: $n = 16$ interventions aimed to promote a shift from cars to environmentally friendly modes of transport (walking, cycling, and public transport) by providing information tailored to individual households' interests and requirements and were associated with modest but generally consistent net increases in cycling trip frequency. Other interventions that targeted travel behaviour: A sustainable transport public awareness campaign involving leaflets, mass media, exhibitions and talks in schools in the context of improvements to local transport infrastructure saw modest increases in cycling. A car-share initiative saw small decreases in cycling. A financial incentive intervention for not using a car-parking space reported a very small increase in cycling.
Bauman (108)	Individual Social Physical environment Policy	An overview of interventions shown to be successful in Australia. These were shown to be; Mass marketing campaigns highlighting the benefits of cycling; Bicycle education programs to increase skills, confidence and safety; Behaviour change initiatives to market alternatives to car use; Cycling events to provide incentives for people to ride in a supportive environment particularly for novice riders; Urban planning; Improved bicycle infrastructure; and funding from all levels of government focused on increasing bicycle friendly design.
Ogilvie (124)	Individual Social Physical environment	A systematic review of studies which attempted to promote walking and cycling as an alternative to using a car. Results typically presented for combined walking and cycling however some evidence was found that targeted programmes led to behaviour change in motivated groups. There was inconclusive evidence for other intervention types such as publicity campaigns, engineering measures and financial incentives.

active travel. These have been found to be effective in shifting trips being made by car to walking and cycling. However, few studies have robustly evaluated individual level intervention solutions for cycling in isolation; these actions are typically included as part of a multi-component or multi-behaviour strategy. Several studies evaluating *individualised travel planning* do report positive findings although it should be noted these typically contain several accompanying social and physical environment actions. There is mixed evidence for the impact of *financial incentives* on cycling although some studies do demonstrate short-term positive effects. There is little evidence that *education and awareness* campaigns by themselves are sufficient to prompt behaviour change. Such campaigns may be an important first step to changing attitudes around cycling, but additional accompanying actions to identify and remove barriers appear to be required.

7.1.2. Social level solutions

At this level, the evidence base is still early in its development. Again, it is often difficult to identify actions that would be considered purely at the social level; there is often overlap with individual level actions or they contribute to a multi-component, community wide project also including changes to the physical environment. Currently, there is insufficient evidence to support the promotion of several potential solutions at this level by themselves in promoting cycling. Such actions include: workplace *transport planning,* one-off large-scale *cycling events* (e.g., a Ride to Work Day), conducting *workplace challenges*, and having *workplace cycling champions*.

Again there are instances where such programmes have been effective, and others where they have not. Whilst such solutions by themselves may not produce behaviour change, they may be useful for the purposes of reinforcing and reminding people about their behaviour, enhancing social support and contributing to the creation of a cycling culture within a community or organisation.

7.1.3. Physical environment level solutions

The strongest and largest body of evidence exists at this level. Early reviews found inconsistent findings in associations between the physical environment and cycling, potentially due to a lack of studies and low methodological quality. More recent reviews reflect the increased research focus on the physical environment as an important determinant of physical activity behaviours such as cycling.

Observational evidence consistently demonstrates that several characteristics related to the design of the physical environment including the *connectivity of streets, distance and access to destinations, and perceived safety* are associated with levels of cycling. There is also emerging evidence that changes to these characteristics are associated with changes in cycling. Most recently, there has been an increase in more robust evaluations of cycling infrastructure projects—both in improvements to existing infrastructure and the creation of new infrastructure.

The evidence is becoming increasingly strong that introducing actions such as appropriate signage, local facilities (bicycle racks, showers etc), dedicated and high-quality cycle paths, comprehensive networks, and traffic calming measures leads to an increase in cycling. It should be noted that such infrastructure improvements may work best when combined with actions at other levels of the socio-ecological model. There is also a substantial body of evidence emerging, demonstrating the consistently positive effects of bicycle hire and sharing schemes within organisations and at wider community and city levels. However, it is important to recognise, as Fell and Kivenen state, that "Infrastructure is generally regarded as necessary but not sufficient to boost cycling" (115).

7.1.4. Policy level solutions

The evidence on the impact of interventions at the policy level is the least developed. Much of the evidence appraised by the key reviews in **Table 3**, proposes potential policies that could be created and implemented based around interventions at other levels of the social-ecological model (i.e., utilising policy-related evidence). For example, using the evidence base around improvements to infrastructure and the physical environment to suggest policies should be generated to improve cycle routes. Similarly, several reviews recommend an increase in government investment in cycling related projects to support attempts to increase cycling but without a formal evaluation of any previous funding strategies. However, there is some mixed evidence which suggests that introducing policy and legislation to lower vehicle speed limits (i.e., introduction of 20 mph zones and limits) may result in an increase in cycling.

7.2. Summary of solutions to increase the number of people cycling

Cycling is a complex, multi-faceted behaviour, with barriers and facilitators operating at multiple levels for different individuals and sub-groups of the population. Accordingly, in order to address these barriers, multiple solutions will be required. What is clearly evident from this overview of the evidence base is that no single intervention, programme or policy will be sufficient to produce long-lasting, population-wide increases in cycling.

Research has demonstrated that it is essential to target both the "*place*" through improving cycling infrastructure at the physical environmental level, and also the "*person*" through individual and social level support. Whilst intervening at the level of the physical environment and improving the infrastructure for cycling is possible and undoubtedly necessary, doing so in isolation is unlikely to be sufficient to prompt behaviour change for many individuals. Thus, what will be needed to best promote cycling has been described as "*a coordinated package of complementary infrastructure measures, programs and policies*" (77). It will also require time following introduction of such packages in order for cycling to become normalised and imbedded in a workplace or in society in general.

However, large-scale infrastructure and national policy changes require substantial financial and political investment and are simply not feasible for several organisations such as schools, business, charities and workplaces who may wish to promote cycling. Therefore, it is imperative that there is further development and a rigorous examination of the types of interventions and programmes that these stakeholders can implement—namely those at the individual and social levels. Critically, this is where the evidence base is weakest and it has been acknowledged that there is "*a paucity of studies that investigate and rigorously evaluate the independent effects of behaviour-based cycling promotion initiatives*" (113).

Table 4 provides a summary of what we know and what is not yet know about how best to promote cycling. The existing evidence base for the promotion of cycling is not complete, and this limits our ability to affect the sort of change that would impact population health. In addition to the limitations of the current evidence base noted above, there are two important reasons why the existing evidence base does not give the full picture.

First, since the evidence base is comprised of what has been studied and evaluated, typically in an academic setting. Therefore, it will always tend to be influenced by what is quick, convenient, and cheap to study and evaluate. It is likely to be further influenced by what is of interest to academic journals and research funders (this is known as publication bias). In short, not all things get evaluated, and not all things that get evaluated make it into journals and reports. The outcome is that the "accepted" evidence base can give a very limited picture of the full scope of approaches.

Second, there are some novel and fast changing approaches, for which the effectiveness is not yet fully understood. These include potential strategies such as; the introduction of e-Bikes (electric assisted bicycles) (125), the use of evolving technologies such as Smart Phone applications (126), and Intelligent Transport using the Internet of Things (127).

There is a need to understand how to increase cycling through interventions that can be delivered effectively, cost-effectively and at scale to benefit population health. For the reasons given above,

TABLE 4 What is known and what is not yet know about how best to promote cycling.

Solutions to promote cycling		
What is known	**What is not yet known**	**What is needed to fill evidence gap**
• Numerous systematic reviews exist which synthesise the evidence from observational and experimental studies and which highlight that there are many potential solutions to promote cycling. These exist across all four levels of the socio-ecological model (individual, social, physical environment and policy). The most likely way to promote cycling is through an integrated package of complementary actions targeting both individuals and their social and physical environments. • The evidence base appears largest and strongest at the level of the physical environment, where emerging evidence from robustly evaluated natural experiments supports the creation of new cycle paths, routes and networks which requires considerable financial investment and political support from local and national governments.	• The current evidence base is built primarily from systematic reviews of studies found in academic journals. Hence, publication bias and a focus on programmes considered easiest to evaluate has likely led to an incomplete picture of how best to promote cycling. Many potential solutions, delivered outside of an academic setting, have not been studied or evaluated. Additionally, there are several novel potential solutions emerging for which the effectiveness is not yet understood. • Where the evidence base is less abundant and consistent is at the individual and social levels of the socioecological model. Some evidence exists for targeted behaviour change programmes but the evidence is inconclusive for interventions such as financial incentives, counselling and education and awareness raising. There have been few rigorous evaluations of the independent effects of such efforts to promote cycling yet these are the types of programmes that organisations such as schools and workplaces can implement.	• There is a need to build a comprehensive picture of all potential solutions to increase cycling, at the levels appropriate for delivery by organisations such as workplaces. Whilst such solutions may be considered smaller in scale than large infrastructure projects, they could still be delivered nationwide across workplaces, communities, and schools. They may also encourage the use of existing infrastructure. They are therefore undoubtedly an essential component of the integrated package of measures that will be required to increase population levels of cycling. • A comprehensive picture is required to highlight the most promising, novel and feasible solutions to take forward for subsequent pilot and preference testing. It will be necessary to examine these solutions for their potential in addressing the barriers to cycling faced by different individuals and population sub-groups.

it is important to look beyond what is already evaluated and deemed effective. It is clear that a critical next step is to build the evidence base in terms of possible approaches to promote cycling. An efficient way to do this would be to undertake a scoping review of all existing approaches utilising traditional electronic record searching, and importantly the databases of key cycling promotion organisations, and expert stakeholder consultation. This would generate a more comprehensive evidence base, identifying interventions which have been rigorously evaluated and published and also interventions which have not been evaluated but may provide alternative and potentially novel solutions to promote cycling. This would facilitate mapping of the actions and functions of the different intervention approaches (the active ingredients) as well as specified intervention characteristics including; duration (how long the intervention lasts for), scale (at level of socio-ecological model), setting (e.g., workplace, community, school, etc.), and target population (e.g., adults).

A conceptual version of this is presented in **Figure 3**, which maps intervention actions against the socio-ecological model. It is apparent from this figure that moving up the socio-ecological model into Physical Environment (yellow) and Policy (pink), the implementation of the actions requires greater resource and influence. As stated, actions at these levels are likely to be necessary, but not sufficient, to induce substantial shifts in cycling participation at the population level, and actions at the Individual (green) and Social (blue) levels are also likely to be needed. Thus, a map of potential interventions across the socio-ecological model will enable identification of actions which are feasible for implementation by organisations, workplaces, schools, and local stakeholders and can complement interventions at the level of policy and the macro-physical environment and provide the base for preference testing and ultimately intervention piloting, on the route to creating an evidence based tool-kit for promoting cycling.

7.3. Case study: the cycle nation project

In recognition of the need to address barriers at different levels of the socio-ecologial model, the Cycle Nation Project (CNP) aimed to develop, test the feasibility of, and optimise a multi-component workplace-based intervention to increase cycling among office staff at a multinational bank (107). To ensure that the most appropriate strategies were utilised in the intervention, focus groups were conducted with bank employees to understand any context-specific barriers and ways in which these might be overcome. This led to identification of 10 individual-level, two social-level, and five organizational-level modifiable factors, which were mapped to candidate intervention components previously identified in the Kelly et al. scoping review of cycling initiatives (5). The resultant pilot intervention included 32 core components across six intervention functions (education, persuasion, incentivisation, training, environmental restructuring, enablement). Participants received a loan bike for 12-weeks (or their own bike serviced), and a 9-week cycle training course (condensed to 6 weeks for those already confident in basic cycling skills), including interactive information sharing activities, behaviour change techniques (e.g., weekly goal setting), bike maintenance training, practical off-road cycling skill games and on-road group rides. To address the sustainability of the intervention, sessions were delivered by trained bank staff members who were experienced cyclists.

The CNP pilot intervention was delivered across three sites with 68 participants. It was completed in two sites (the third site was stopped due to COVID-19) and was feasible and acceptable to both women and men and across different ethnicities. In addition, the CNP intervention was successful (at least in the short term) in increasing cycling by 3 rides/week on average, and improving perceptions of safety, vitality,

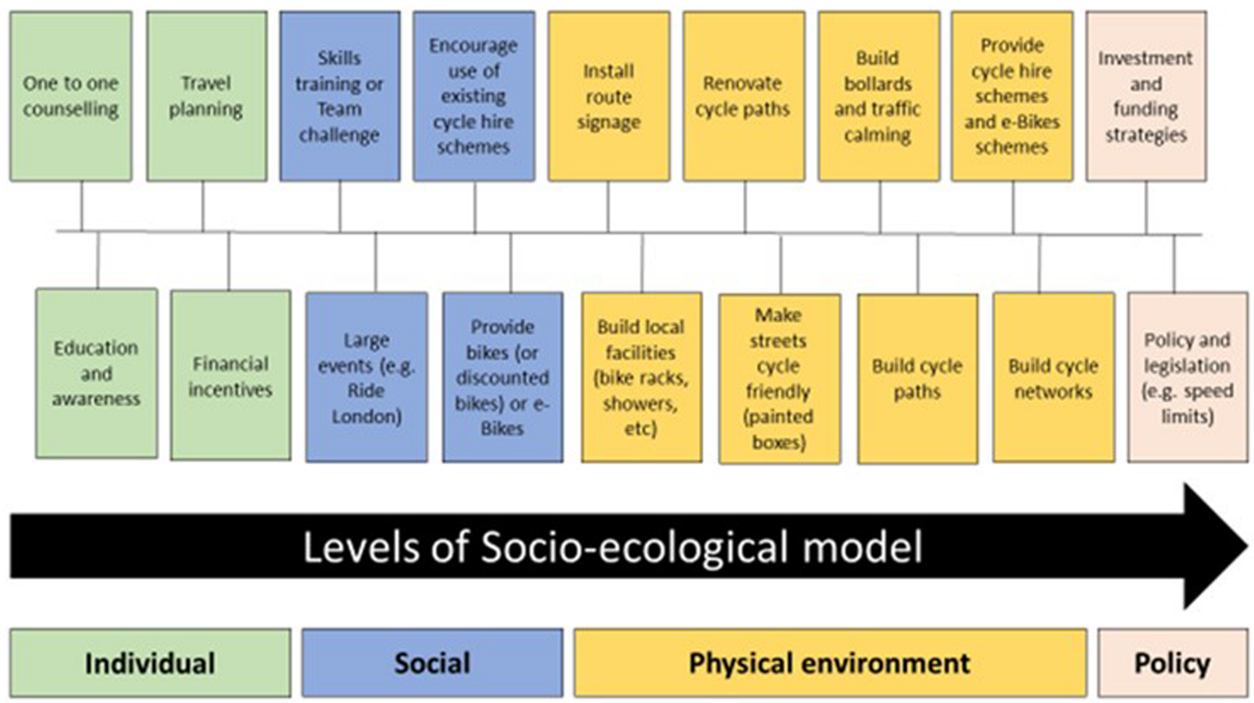

FIGURE 3
Interventions and actions to promote cycling mapped on the socio-ecological model.

confidence, and motivation to cycle (107). This case study affirms how targeted intervention strategies can be applied to specific populations to successfully improve cycling behaviours. For successful large-scale rollout, there is need for development and evaluation of interventions, like the CNP, which use multi-component strategies.

8. Summary

Given the potential positive impact sustained uptake in cycling can have on public health, wellbeing, the economy, and the environment, it is important to invest in effective solutions to improve cycling behaviour. Although still in its infancy, research insights into behaviour change strategies show potential to foster increased cycling levels when applied to target populations. From reviewing the available literature, we observed that programme design for interventions to increase cycling may be most effective when a multi-component approach is utilised. Therefore, there is further need to develop and evaluate multi-component cycling interventions for successful large-scale application to maximise cycling uptake.

Author contributions

JG, CG, PK, GB, and EM contributed to conception and design of the study. All authors contributed to the article and approved the submitted version.

Funding

This work was supported by a Research Grant from British Cycling and HSBC UK.

Acknowledgments

We would like to thank Allison Coles and Sarah Broadfield from British Cycling for work in development of the Cycle Nation Project.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The nature of the Cycle Nation Project meant that the funders, British Cycling and HSBC UK, were intimately involved as representatives in this review. All analysis was performed by the authors without input from British Cycling or HSBC UK.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fspor.2023.1168357/full#supplementary-material

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frontiers | Frontiers in Sports and Active Living

TYPE Original Research
PUBLISHED 29 September 2023
DOI 10.3389/fspor.2023.1150724

OPEN ACCESS

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RECEIVED 24 January 2023
ACCEPTED 11 September 2023
PUBLISHED 29 September 2023

CITATION
Bourne JE, Leary S, England C and Searle A (2023) "I felt marvellous e-cycling. If I had long hair I would have flicked it": a qualitative investigation of the factors associated with e-cycling engagement among adults with type 2 diabetes.
Front. Sports Act. Living 5:1150724.
doi: 10.3389/fspor.2023.1150724

"I felt marvellous e-cycling. If I had long hair I would have flicked it": a qualitative investigation of the factors associated with e-cycling engagement among adults with type 2 diabetes

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Background: Physical activity (PA) is a key component in the management of type 2 diabetes. However, this population have low rates of PA engagement. Electrically assisted cycling has been identified as a means through which to increase PA by incorporating activity into daily life, while overcoming some of the barriers to conventional cycling. The determinants of e-cycling among people living with chronic disease are largely unknown. The aim of this research was to explore the determinants of e-cycling among individuals with type 2 diabetes using the Theoretical Domains Framework (TDF) and the Capability, Opportunity and Motivation for Behaviour change model (COM-B). This information is important for determining the suitability of future e-cycling initiatives and, if appropriate, inform future e-cycling interventions.

Method: One-to-one semi structured interviews were conducted with 16 participants from the e-cycling arm of a pilot randomised controlled trial between September 2019 and April 2020. The TDF was used to develop the interview guide. The framework method of analysis was used, incorporating both deductive and inductive reasoning. A conceptual model of the factors that influence e-cycling in this population was created.

Results: The most commonly reported TDF domains were skills, knowledge, belief about capabilities, belief about consequences and environmental context and resources. Specifically, e-bike training facilitated e-cycling engagement by providing participants with the skills, knowledge, and confidence needed to ride the e-bike and ride on the road. In addition, the enjoyment of e-cycling was a key facilitator to engagement. Participants engaged in e-cycling to improve their health rather than for environmental reasons. Most barriers to e-cycling related to the natural or physical environment.

Conclusion: This study provides insight into the personal, social, and environmental factors associated with e-cycling in this population. The findings of this study can be used to develop a more refined e-cycling intervention targeting the factors identified as influencing e-cycling engagement. In addition, this information will help in the selection of mechanistic outcome measures for evaluation.

KEYWORDS

e-cycling, perceptions, physical activity, type 2 diabetes, qualitative

1. Introduction

Type 2 diabetes is a metabolic disease that negatively impacts an individual's physical and mental health (1–6). By 2040, it is estimated that approximately 642 million individuals worldwide will be diagnosed with diabetes, of which 90% will be type 2 diabetes (7). The cost of ongoing treatment and management of type 2 diabetes and its associated complications places considerable strain on health services (8).

Physical activity (PA) is an important lifestyle factor in the prevention and treatment of type 2 diabetes (9–13). However, individuals with type 2 diabetes are less physically active than those without type 2 diabetes and many fail to meet the recommendation of 150-min of moderate to vigorous physical activity (MVPA) per week (14–16). Interventions aimed at increasing PA in this population often require significant contact time and expertise, thereby limiting their scalability (17). Furthermore, individuals often return to prior PA levels when left to self-manage their activity (17–19). As such, there is a need to develop PA interventions that are less labour intensive and that are effective at promoting behaviour change beyond the intervention period.

Active travel is widely recognised nationally and internationally as a means of increasing PA. As such, encouraging active travel is endorsed by the National Institute of Health and Care Excellence (20) and the World Health Organization (21). Among individuals with type 2 diabetes active commuting is associated with increased PA and lower body mass index (22). Despite widespread endorsement, rates of engagement in active travel in the UK and around the world are low (23–25), especially among individuals living with type 2 diabetes (22). Community-based initiatives can serve to increase cycling behaviour (26–29), however it is rarely maintained over time (30, 31). Furthermore, there are several barriers to conventional cycling that could discourage engagement including physical constraints associated with hilly terrain and poor physical fitness, as well as a lack of time and the distance people have to travel (32). These barriers may be accentuated in individuals with type 2 diabetes given their overall lower levels of PA.

Electrically-assisted bicycles (e-bikes; also known as pedelecs) have been identified as an alternative form of active travel that can positively impact health (33) while overcoming some of the commonly reported barriers to conventional cycling. While e-bikes have many similarities with conventional bicycles, the electrical assistance requires less physical effort and leads to greater riding distance and frequency (34–36). Therefore, it is likely that some determinants of conventional cycling are less relevant to e-cycling. Despite the electrical assistance evidence suggests that e-cycling is performed at at least a moderate intensity and leads to similar or slightly lower physical markers of intensity than conventional cycling (33). However, given that individuals report e-cycling for longer and more frequently than they do a conventional bicycle, e-cycling is often associated with greater weekly energy expenditure than a conventional bicycle (35, 37).

Research conducted with e-bike owners and those who have been provided with an e-bike as part of an intervention reveals that the ability to ride further, faster, on hillier terrain and to ride with friends and family are common facilitators to e-cycling engagement. Conversely, bad weather, poor infrastructure and theft concerns are common barriers to engagement (34, 36, 38–40). To date, few studies have explored the factors associated with e-cycling among people living with chronic disease for whom engagement in active travel is low (22). People living with chronic conditions may experience e-cycling interventions differently and be impacted by different contextual factors than a healthy adult population. Two studies have specifically explored factors associated with e-bike engagement in people living with chronic disease. Boland and colleagues (41) examined the use of adapted e-bikes in three individuals recovering from a stroke. The level of social support, motivation for riding, level of physical impairment all impacted riding. Among individuals with type 2 diabetes, Searle and colleagues (42) reported that e-cycling was perceived as enjoyable and enabled individuals to cycle with friends and family. However, they did not conduct a comprehensive evaluation of the data to explore the determinants of e-bike use, rather the researchers were interested in understanding how e-cycling impacted participants management of their diabetes. E-cycling may offer an alternative to structured lifestyle interventions for individuals with type 2 diabetes, enabling exercise to be completed outside and incorporated into daily life which may lead to sustained physical activity behaviour.

Understanding how participants experience e-cycling, particularly the barriers and facilitators to riding, will enable the development of a conceptual understanding of the factors that are most influential on e-cycling engagement in this population. The use of behaviour-change theory and models can help in this understanding and identify key intervention components required to bring about change. The Medical Research Council guidance for developing complex interventions outlines that researchers need to have a theoretical understanding of the potential processes of change (43). When little is known about the target behaviour in the population of interest qualitative research is useful to develop a theoretical understanding of the behaviour (44). The Behaviour Change Wheel is a practical intervention design tool which transparently guides researchers through intervention design and delivery. At the core of the BCW is the COM-B model which can be used to determine what needs to change for the desired behaviour to occur (45). The COM-B model proposes that human behaviour is a result of the interaction between capability, opportunity and motivation. Specifically, for a behaviour to occur a person must have the psychological and physical capability to perform the behaviour; the physical and social opportunity to engage in it; and they must have the motivation, either conscious or automatic, to engage. COM-B has been found to be an effective model in explaining physical activity behaviours (46).

The Theoretical Domains Framework (TDF) was designed to understand behaviour theoretically by establishing which processes of change should be targeted (47). The TDF consists of 14 theoretical domains that consider the environmental, social, cognitive and affective influences on behaviour (48). The TDF maps directly onto the COM-B components, enabling expansion of each of these components and assisting in identification of the potential determinants of behaviour. Once identified, this information can be used to guide the selection of quantitative measures to examine potential moderating and mediating effects as part of a full-scale evaluation and/or to inform target areas for intervention in future e-cycling initiatives among individuals living with chronic disease. The primary objective of the study was to explore the factors associated with e-cycling engagement among individuals with type 2 diabetes following trialling an e-bike using the TDF and COM-B model, and to develop a conceptual model of the behaviour.

2. Methods

2.1. Participants and procedures

One-to-one semi-structured interviews were conducted with individuals who were randomised to the intervention arm of a parallel two-arm pilot randomised controlled trial. The trial compared an e-cycling intervention against a standard-care waitlist control in adults with type 2 diabetes (49). Eligibility for the study included having a clinical diagnosis of type 2 diabetes and being between 30 and 70-years of age. Individuals were ineligible if they self-reported engagement in ≥150-min of MVPA per week (50); took exogenous insulin; had a myocardial infarction or stroke in the past six months or had evidence of end-stage renal failure or liver disease; had uncontrolled hypertension; had any other contraindications to exercise; were not cleared to engage in PA by their GP and/or were unable to read and communicate in English. This single centre study was conducted in the city of Bristol, England. Individuals in the intervention arm received e-bike training consisting of two one-to-one training sessions followed by a 12-week e-bike loan in which they were instructed to use the e-bike as they desired (i.e., no riding goals stipulated). During the e-bike loan participants were offered two further training sessions. Twenty individuals were allocated to the intervention arm. Four participants discontinued with the intervention (reasons included: personal situation [$n = 2$], purchased an e-bike [$n = 1$], undisclosed [$n = 1$]). Seventeen individuals were invited to take part in the interviews of which 16 participated. Interviews were conducted by JEB over the telephone between September 2019 and April 2020, within two weeks of finishing the e-bike trial. The interviews were digitally recorded using encrypted recording devices. The recordings were transcribed verbatim by Transcription UK and stored using NVivo data management software (NVivo10, QSR International, 2012). The transcripts were checked against the original recordings to ensure reliability. Interviews ranged between 33mins and 50mins in length. Ethical approval was obtained from the NHS Health Research Authority Southwest/Central Bristol Research Ethics Committee (Ref: 18/SW/0164) and was sponsored by the University of Bristol.

2.2. Interview questions

The interview topic guide was developed using the Theoretical Domains Framework (TDF) (48) and based on guidance by Atkins and colleagues (51). The interview guide included at least one question for each theoretical domain to comprehensively consider the possible influences on e-cycling. The interview guide is provided in the **Supplementary Material**. Follow-up probes or prompts were included to delve more deeply into each domain (51). The order in which questions were asked was flexible to enable flow during the interview.

2.3. Qualitative data analysis

Interview data were analysed using the Framework method (52) and guided by Gale and colleagues seven-stage analysis process (53). The Framework method sits within the family of analyses methods known as 'thematic analysis" (53, 54) and is suited to research that has specific questions and a pre-defined sample (55). Framework analysis does not require adherence to either inductive or deductive analysis approaches and is therefore appropriate in the current theory-based study. In addition, it does not prescribe to a single epistemological or ontological framework thereby providing a degree of flexibility regarding how data analyses is approached (54). **Table 1** outlines the steps involved in analysing the data. JEB created the e-cycling intervention as part of her PhD research. She had training in qualitative research methods, developed the interview guide and conducted the interviews. JEB analysed the data with in-depth discussions with AS. In the current study a critical realist ontology and constructionist epistemology was adopted regarding the data.

3. Results

3.1. Participants characteristics

Of the 16 participants interviewed, there was an equal split between men and women and a mean age of 59.75 years (Standard Deviation = 6.85). Ten participants were working either full or part time. Fourteen participants had some degree of cycling experience prior to the trial. Overall 56.25% of participants completed three or more cycling lessons with the instructors. Fifteen participants had at least one private vehicle at their residence. The distances travelled on the e-bike during the loan period by the 13 participants with available data ranged from 9 km to 1,878 km (Median = 144.4; IQR: 117.0, 307.0), with a median of 22 journeys (IQR: 13, 33) over the loan period based on travel log books. **Table 2** provides the demographic characteristics of participants.

3.2. Summary of the TDF and COM-B model

The transcripts provided data that represent all the fourteen domains of the TDF and all components of the COM-B model. **Table 3** presents a summary of COM-B constructs, TDF domains and frequency counts, themes and example quotes. Whether the theme was identified as a barrier or facilitator to

TABLE 1 The seven stages of the framework method of qualitative analysis and how they were applied to the research question.

Procedure for analysis	Application in the current study
Stage 1. Transcription	All interviews were conducted by JEB and transcribed by Transcription UK. The transcripts were checked against the original recordings to ensure reliability.
Stage 2. Familiarisation	JEB listened to each audio recording and read each transcript. AS read two interview transcripts. The transcripts were selected by JEB to represent diverse experiences of e-cycling.
Stage 3 and 4. Development of analytical framework and coding	Excerpts of the two transcripts were deductively assigned into one or more of the 14 domains reflected in the TDF and directly onto the six components of the COM-B model (content analysis). Excerpts that were deemed important but did not fit into one of the 14-domains were placed in an 'other' category. This was done independently by JEB and AS who met to discuss assignment. Following this, inductive coding within each TDF domain took place to identify themes. Codes were noted as either a 'barrier' or 'facilitator' depending on the context in which the code occurred. These were operationalised as any factor, characteristic, view or belief that either impeded or enabled e-cycling engagement. This was done independently by JEB and AS who met to discuss assignment and an analytical framework was developed. The two researchers independently coded two more transcripts, noting any new codes. The researchers met again to discuss the coding and to revise the initial framework to incorporate new or redefined themes.
Stage 5. Applying the analytical framework (Indexing)	JEB used this framework to code the remaining transcripts using NVivo software. If a new theme was required, this was discussed with AS before adding it to the analytical framework. If a new theme or domain (which did not fit the TDF) was added, previously coded transcripts were checked for relevant data.
Stage 6. Charting data into the framework matrix	After finalising themes, TDF domains and COM-B constructs, a framework matrix was developed. NVivo was used to create matrices that encapsulated data from each domain and sub-domain. Following this, each participants data was described and summarised to develop a chart. This was conducted in Excel and consisted of participants in rows with summaries of domains and sub-domains in columns. AS checked the summaries of the first two transcripts to ensure they captured the essence of the data. Two participants were provided with a copy of their interview transcript and an interpretation of their data. They were asked to review their transcribed data and comment if they felt the interpretations represented or misrepresented their views.
Stage 7. Mapping and interpreting the data	Summative content analysis (56) was applied in which the frequency count of each theme was calculated. TDF domains, and associated COM-B constructs, were judged based on the frequency count of coding for each TDF domain. This frequency coding enabled the identification of the main barriers and facilitators to engaging in e-cycling in this population. The significance and implications of the domains, and how they relate to one another was examined narratively, and a conceptual model of the factors that impact e-cycling in this population was developed.

TABLE 2 Demographic characteristics.

Variable	*N*
Age, years, mean (SD)	59.75 (6.85)
Sex, %	
Female	8 (50)
Male	8 (50)
Ethnicity, %	
White	15 (93.75)
Asian	1 (6.25)
Employment status, %	
Full-time (35 h or more per week)	7 (43.75)
Part-time	3 (18.75)
Unemployed	1 (6.25)
Retired	5 (31.25)
Previous cycling experience, %	
None	2 (12.5)
A little	9 (56.25)
A lot	5 (31.25)
Number of journeys, median, IQR	22 (13, 33)
Distance ridden, km, %	
0–99	3 (18.75)
100–199	5 (31.25)
200–299	1 (6.25)
300–399	2 (12.5)
400–499	0 (0)
500+	2 (12.5)
Distance not available	3 (18.75)

e-cycling engagement is reported. The COM-B constructs, TDF domains and how they relate to one another are summarised narratively and a conceptual model proposed (**Figure 1**).

The most commonly reported domains were skills, knowledge, beliefs about consequences, belief about capabilities and environmental context/resources, and the least commonly reported domains were optimism, goals and behavioural regulation.

3.2.1. Capability

***Physical capability:* skills**

Fifteen participants were able to ride the e-bike by the end of the training period. Of these 15, 14 had some degree of previous cycling experience. Participants with more recent cycling or motorcycling experience (two to three years) reported greater ability to ride the e-bike than those with no experience or who had not ridden for a long time (**Table 3**.1.a.iii). While several participants engaged in frequent cycling at a younger age, and reported confidence riding a bicycle, many were surprised at how different e-cycling was to conventional cycling. This was attributed to the devices themselves, the poor conditions of the roads and the amount of traffic compared to when they used to cycle. As such, some participants felt their previous riding skills did not translate to e-cycling in the present day.

Before starting the e-bike training participants with previous cycling experience felt that the training was going to be unnecessary. However, all participants reported learning new skills, specifically how to handle the e-bike and use the electrical assistance, and how to ride safely on roads and in traffic (**Table 3**.1.a.i/ii). The training conducting during the loan period enabled participants to practice their skills.

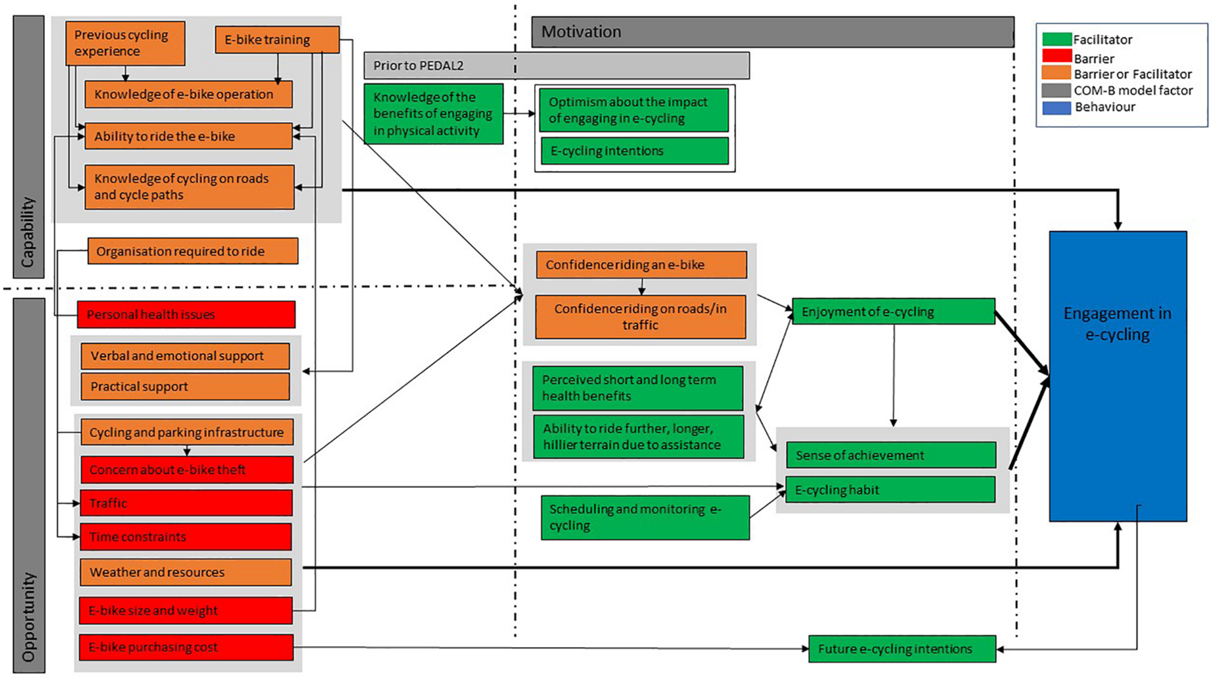

FIGURE 1
Conceptual model of e-cycling in adults with type 2 diabetes.

Psychological capability

Knowledge. The majority of participants were aware of the benefits of engaging in PA, in general, and for diabetes management (Table 3.2.b.i). Several participants felt that engaging in PA was an easier way of managing their diabetes than dieting. This knowledge impacted their desire to sign up for the trial and engage in e-cycling.

The e-bike training provided participants with sufficient knowledge on how to use the e-bike. Over time, with practice, participants became more efficient at using the gears and electrical assistance (Table 3.2.b.iv). In addition, the training taught participants how to safely ride on the road and where to find safe cycle paths (Table 3.2.b.ii/iii). When choosing where to ride some participants reported sticking to familiar routes, for which they knew the cycling infrastructure and/or traffic levels. While others enjoyed using the cycling maps to plan rides and explore new bike paths (Table 3.2.b.ii).

Behavioural regulation. Although infrequently discussed, some participants reported that monitoring their behaviour using tools such as Strava or a GPS watch encouraged them to engage in e-cycling.

Memory, attention and decision making processes. Participants reported evaluating the pros and cons of cycling vs. using a different mode of transport (Table 3.2.d.ii). As such, the decision to engage in e-cycling was often carefully considered. In general participants felt that utilitarian journeys required more organisation than recreational journeys. However, participants who had cycled regularly in the past reported having strategies to ensure they would remember all the required equipment, such as prepacking bags or running through mental checklists before leaving to ensure they had all their equipment (Table 3.2.d.i).

3.2.2. Opportunity

Physical opportunity: environmental context and resources

Barriers relating to the physical opportunity were the most commonly reported by participants in this study and included:.

Cycling infrastructure, parking facilities and traffic. Participants were concerned that the e-bike could be stolen if left in a public space, especially when the parking facilities were deemed inadequate (Table 3.3.e.viii). Theft anxiety was exacerbated as the e-bike was on loan and participants were unclear of the financial implications for themselves if the e-bike was stolen. Participants reported that they would have been less anxious about locking the e-bike up in public spaces if it belonged to them. Having good parking facilities at a destination facilitated e-cycling, particularly for utilitarian purposes, while poor parking facilities inhibited e-bike use (Table 3.3.e.i). Having limited e-bike storage at home also inhibited e-cycling. Several participants had to keep the e-bike indoors which meant getting in and out the house required considerable effort (Table 3.3.e.i).

Regarding riding, participants were reluctant to ride on roads with no cycling infrastructure, primarily due to traffic concerns (Table 3.3.e.vii). Participants who felt they were close to segregated cycle paths were willing to cycle short distances on the road to reach these paths. Participants' level of confidence riding the e-bike and riding on roads impacted the degree to which segregated cycling infrastructure was deemed a necessity.

TABLE 3 COM-B constructs, TDF domains, sub-themes and example quotes.

COM-B construct	TDF domain (frequency count)	Sub-themes (frequency count) (Barrier or facilitator)	Example quote
1. Physical capability	a. Skills (107)	**i. Ability to ride and manoeuvre the e-bike** (35) (B, F)	*So at first I was wobbly, even riding round the park I was wobbling. Then, after that, you just got used to it, and it was like just round, and round, and round. It was fine, got on really fine* (P6, no cycling experience); *I found it was different to my ordinary bike in that I was… oh, how do I explain this? I was nearer the handlebars so my legs were going up and down, rather than forwards, if you see what I mean? So, I didn't like* (P14, lots of cycling experience)
		ii. E-bike training was helpful or insufficient (40) (B, F)	*Oh, yes. That* [the training] *was really useful actually because I was a bit, you know, "I don't need to do this," kind of, thing "I've always cycled, I don't need to be shown what to do." But it was actually quite useful just to do some basics'* (P2, lots of cycling experience); '*It was all a bit quick, but I mean- And I thought they should have said something about more training at a later date'* (P15, a little cycling experience)
		iii. Impact of previous cycling experience (22) (B, F)	*I had a desire, I had no experience, even in the standby bicycle, or nothing. I think the electronic bike was so heavy and not manageable* (P10); *Well I ride a motorbike anyway, so I'm not unconfident on a road on a bike.* (P1); *In my younger days, I did quite a lot of cycling, so it all seems fairly familiar to me* (P11); *I used to commute but I would say that was say 12 years ago, that was when I lived in London. So, I was a bit surprised how absolutely terrified I was* (P4)
2. Psychological capability	b. Knowledge (141)	**i. Benefits of physical activity** (40) (F)	*Well, every time that you go for a review, they will say, "Losing weight is going to be beneficial. Getting fitter is going to be beneficial," but it's easier said than done* (P12); *I've only been diabetic for two years. And I think what I'm finding is that it's actually harder than I expected to keep your blood sugars down. It's [exercise] a really positive way of doing that because just to control it through diet is really quite challenging* (P2)
		ii. Familiarity with cycle routes (15) (B, F)	*'Because cycling out there seems to have got better, as in you've got paths to go on, and I found some really interesting paths'* (P3); '*I tended to have a particular circuit that was around the XX. Even if it was just forty-five minutes so I had a particular circuit around the XX* (P2)
		iii. Knowledge of riding on roads (33) (B, F)	*Training, I feel that was very good at pointing out what you should do at junctions and double checking you're aware of everything and making sure you were looking both ways. Looking and listening and looking again, I think, is very important and they definitely reinforced that.* (P11).
		iv. Understanding of how to operate the e-bike (23) (B, F)	*'When I first started, I was flicking the buttons all the time. But then I realised that you don't have to do that, the bike will kick in by itself. That was absolutely fantastic, I really enjoyed that function. If things got a little bit tricky, it would just kick in and you'd go up a gear and it was brilliant'* (P7); *It took me a good few sessions to sort of get to used to it, the fundamental use of it and how and when to deploy the gears and what have you, and the assistance. But once I got into that pattern, it wasn't too much of a problem* (P16).
	c. Behavioural regulation (9)	**i. Using technology to self-monitor rides** (9) (F)	*'I go on Strava and you put it on and you get personal records when you do a ride. If I did a trip 20 times, every day I'd have a personal best in there somewhere. And at the hill, there is like 0.1 of a mile up the hill and you get a record, but you knew you did because you were really pushing it. When you get there, you think, "Oh, I actually got the best time.'* (P12)
	d. Memory, attention and decision processes (67)	**i. Remembering to charge e-bike or specific equipment** (18) (B, F)	*'I wore the helmet all the time, and I went into work and I was coming out and I was like a mile or two miles home and I always wore glasses as well. I could just feel the wind in my hair and I thought, "I haven't got my glasses on. I haven't got my helmet on either.'* (P12, a little cycling experience); '*You just got used to getting your bag. Well, the bag was half packed anyway. And I would always take the lock for it. I would always take that with me'* (P3, a little cycling experience): '*When I go out anywhere I come home and then I put it straight onto charge, and then it's fully charged'* (P5, a little cycling experience)
		ii. Decision to engage in e-cycling (48) (B, F)	*'I would say that commuting was definitely one reason to get me out on the bike, because it was just very easy to get to work. Where I work is in the middle of town and there isn't any parking allowed, except for special reasons where you have to book it a long time in advance and give a definite reason. There are only four parking spaces for the company, and I think there are probably about 200 employees in the company. All around there the car parking is very, very expensive. So, let's look at it from the other side, the next choices are taking the public transport and the buses are often very full at that commuter time and often go straight past you. So, you can end up not getting the bus. The other option is to walk or drive down to the local train station and, again, the train is very crowded. The final option is to get on the bike, go through a couple of back roads and get on the cycle path, whizz down the cycle path, cross over one major road and then some minor back-roads and there's plenty of bike parking in the cellar of the building and it's secure and monitored with cameras and locked with barriers and automatic gates, so that the bikes are very safe there, so you've got no worry about that. In that respect, it is the best option'* (P11)

(*Continued*)

TABLE 3 Continued

COM-B construct	TDF domain (frequency count)	Sub-themes (frequency count) (Barrier or facilitator)	Example quote
3. Physical opportunity	e. Environmental context and resources (265)	**i. Access to infrastructure for riding and parking** (88) (B, F)	*'The only thing storing the bike, I had to put it in the kitchen because I live in a high rise flat, and there's nowhere else to put it'* (P5); *We've got a car park, which is locked. There is an interlock on the back wheel, so I lock that, took the battery off, put the D lock around a fixed clamp, took all the computer off, took the lights off, took the pannier in and left it like that* (P12); *'The main way I would have gone into work would have been to go down XX Road. And I don't think there's a cycle lane there and it's very, very busy so… It's put me off. Really'* (P2); *'When I'm on early shift, I get up early and I just stick to the roads because I'm not overly confident going on the cycle path at five in the morning in the pitch dark, and coming back at night, I don't really want to be on there at ten or eleven o' clock either, just all the wispy shadows and people stood behind the bridges and that, it's just a little bit concerning, but I am fine on the roads'* (P12); *That was quite difficult actually* [a particular cycle path] *because it was shared as a footpath. I seemed to be coming across pedestrians every hundred yards'* (P2).
		ii. E-bike size and design features (51) (B)	*'I think the electronic bike was so heavy and not manageable'* (P10); *'It was too high, because I didn't feel comfortable not being able to put my feet flat on the floor, so I had to wait for a seat, because the first seat, still my feet didn't touch the floor. Yes, because obviously where I haven't rode a bike, I needed to be able to put my feet on the floor'* (P6); *'It was a bit of a pain when you had to… when you locked it up, especially when you were out shopping, to take the battery out, you know, take it off and… because it's quite heavy'* (P1)
		iii. E-bikes are expensive to buy (10) (B)	*'I'd never ridden an e-bike and it was really good. When I had to give the e-bike back I tried to use my normal bike and I couldn't use my normal bike and I was struggling with it. So, I'm going to sell that one and save up for an e-bike, it's really hard trying to get an e-bike because it costs so much money'* (P5)
		iv. Impact of weather and resources 51 (B, F)	*'Because the weather was really bad lately and I couldn't go on the e-bike, so I had to go on the bus to get to places'* (P5); *'So the weather, I guess, the only thing that impacted on me later on was in September. Later in September and early October, where it was dark by the time I got home. I didn't enjoy cycling in the dark very much. I did do it sometimes, but not a lot'* (P2); *I did buy waterproofs. How were they? They were alright. They did the job. I was quite pleased with the clothing I bought, it kept the rain out, yes* (P7).
		v. Personal health issues that impacted riding (26) (B)	*'Well the only other barrier I had was this operation I had. The lead up to it I was told not to overdo it and then the operation itself'* (P1); *'I had an abscess on my tooth, and then I had to have it come out, that impacted riding'* (P6)
		vi. Time constraints (24) (B)	*'The extra work I was doing at work, I was also tired. I'd always come home, have dinner and a bit of a sleep. So, by the time, say, I felt like going on the bike, it was blinking dark at 4:00pm'* (P13)
		vii. Traffic concerns (43) (B)	*Now the roads are getting so busy now with cars and buses, I feel like I'm worried that I'm going to get knocked by a bus or a car* (P5)
		viii. Concerns about e-bike theft (21) (B)	*'I mean, I have got sisters that live about a mile and a half away, and I didn't even want to go up and see them in it because there was nowhere to put the bike safely. Even with the lock, I wasn't happy about it, you know'*(P15)
4. Social opportunity	f. Social influences (72)	**i. Practical support** (46) (B, F)	*'No, no, because [partner] used to walk the dogs while I rode around the park. He was always there, so he'd take the dogs, because he'd take the dogs every day anyway, round the park, so he used to do it when I would go'* (P6, female, no cycling experience); *'I'm more than happy [to cycle alone], I can stop as and when it suits me'* (P16, male, lots of cycling experience). *'Well it would be nice to have a family event. We haven't had a family event like that for a long, long time. It would be nice to get out and do things together'* (P7, female, lots of cycling experience); *'Then in the end we went round Bedminster and I don't think I would have ever cycled around Bedminster without the instructor* (P7).
		ii. Verbal and emotional support (29) (B, F)	*'I think generally positive feedback helps make you, you know, if you are feeling a bit doubtful about whether it was something that was the right thing to do for someone of my age, for example, then that positive feedback probably helped me get over that'* (P2); *I tried it one more time, just local, but yes, by then I think friends were saying to me they thought it was too risky and I shouldn't do it'* (P4); *'The instructor was very good. The second lesson where we went for maybe a 45-min ride on the road and the cycle paths, that was good, and they're always there for help'* (P12)
5. Reflective motivation	g. Optimism (15)	**i. Optimistic that e-cycling would positively impact health** (15) (F)	*'I'm hoping cycling will help* [manage diabetes]. *I've always tried to do a bit of exercise. But I've also cut back on one of my medication as a result of health problems, so I'm hoping that this is going to equate to the extra Metformin'* (P1); *'It was all health [the reason for signing up to the study]. I wasn't really thinking about the environmental factor, at all. I just thought it was something I needed to do'* (P16); *'But [Instructor 1] was very good. The second lesson where we went for maybe a 45-min ride on the road and the cycle paths, that was good, and they're always there for help. If you did have a problem, they're always at the end of the phone'* (P12)

(*Continued*)

TABLE 3 Continued

COM-B construct	TDF domain (frequency count)	Sub-themes (frequency count) (Barrier or facilitator)	Example quote
	h. Beliefs about consequences (122)	**i. Ability to ride further, longer, hillier terrain and new routes** (31) (F)	*'I mean, even the steepest hills were easy enough to go up on the e-bike, you just turn down the gears and put on the turbo'* (P1);*'In the knowledge that I had the assistance, I would tackle routes and push myself a bit further than I would normally on my own cycle'* (P16)
		ii. Environmental and financial impact of e-cycling (31) (F)	*It saves money because I don't have to find bus fare. So, it will have a financial impact when I buy one, but after that I think I would definitely save money.* (P7)
		iii. Long- and short-term health benefits of e-cycling (60) (F)	*'Yes, my legs are definitely stronger than what they used to be. I've got more energy to do things'* (P7); *'I had more stamina through the day riding it. Yes, I felt better. More alive. Usually I just sit, like I'm doing now, on the couch, with the cat and the television on'* (P3)
	i. Beliefs about capabilities (135)	**i. Confidence riding on roads or in traffic** (65) (B, F)	*'I quite happily went out with the traffic. Traffic doesn't bother me that much, as much as I am a driver and I do cycle, so it wasn't much of a problem. I felt confident enough amongst it'* (P16, lots of cycling experience); *I think it decreased [confidence]. Because I think I was a bit taken aback because I had expected to not be nervous, because I've cycled before. So, it was a bit of a surprise. When I headed off to do my journey, I was completely confident, you know, that it wouldn't be difficult. So, it was a bit of a surprise, yes'* (P4, lots of cycling experience).
		ii. Perceived competence riding an e-bike (70) (B, F)	*I have to be honest, I never felt comfortable with the bike that I was given because I found the frame too high'* (P2, lots of cycling experience); *When I started, I found I was more uncomfortable on a bike than I thought. I did find the e-bike slightly heavy to handle so I was a little bit uncomfortable in traffic to start off with. But my confidence grew the more I went out and I think now I'm fairly confident on the bike and it's certainly handling better* (P7, lots of cycling experience); *'As far as riding it is concerned, a little bit lacking in confidence to begin with, because it's quite big and quite heavy and you're quite high up, but over time, I gained my confidence with it and worked out how to use the gears and engine quite efficiently'* (P11, a little cycling expeirence)
	j. Social professional role and identity (29)	**i. Perception of self as a cyclist** (17) (F)	*'My views before, because I am not a cyclist, or I consider myself I am now but before I wasn't a cyclist and I thought I never would. But the trial coming along just gave me that confidence and just changed my total outlook on it, but I do feel I am a cyclist now'* (P12); *'I regard myself more as a cyclist than I did before and if it wasn't for this project I wouldn't have even considered getting out on the bike'* (P7)
		ii. Cycling advocacy (12) (F)	*'I've spoken to quite a few people about them and said, "You've got to give them a go, they're loads of fun and if you don't like cycling, it'll make it a lot easier for you to go back onto a bike". As I said, we've even got one for use of people at work and I keep saying to various people, "Go on, jump on it and have a go, you'll have some fun."'*(P11)
	k. Goal (11)	**i. Planning and scheduling e-cycling** (11) (F)	*I remember in the diary, when I was talking with [the instructor] and I put all my rides in for a 12-week period and then there were targets and I said I'd like to ride to work just once in the trial, if I can get to work.* (P12); *But what I do think I did do was try to achieve targets, so try to achieve, "I'm going to go and see if I can make it to Bath and back and increase the distance. So, I would say I used it less regularly than I thought, but I achieved better targets than I thought I'd be able to do* (P11)
	l. Intentions (81)	**i. Desire to continue riding** (40) (F)	*'I've applied for the cycle scheme and I'm just waiting for the voucher to come through; I've already decided what bike to get, it's a Raleigh Motos Grand Tour. It can do as much as 150 miles on one battery'* (P12); *'Well, again, it's now work hard, save up the money, and get one'* (P13)
		ii. E-cycling intentions (41) (F)	*My intentions were to take it to work. Then when you hear of people having their bikes stolen and I'm thinking, "Hang on a minute'* (P8); *'**At the start of the programme, how did you think you were going to use the bike?** 'Just leisure. I planned to commute once. Then I started going longer and I thought it's a little bit too far to cycle to work and I thought I'd just do it once and then I must have done it maybe a dozen times or maybe twenty times during the trial. I find it a lot easier than I thought it was going to be'* (P12)
6. Automatic motivation	m. Emotion (35)	**i. Riding the e-bike enjoyable and satisfying** (35) (F)	*'There were routes that I chose with the electric bike that I haven't embarked on with my ordinary cycle, despite having it 27 years.... I must admit, I found it quite a rewarding experience'* (P16); *'It's actually a pleasurable experience, riding an e-bike, to be honest, it takes out the grind of going up and down hills, so it takes out the… it makes the difficult parts of cycling become more enjoyable'* (P1); *'I thought it was such a nice morning, I came back through the country route, so I came back over the common. That's how much I enjoyed it. I extended the distance and the time it took me to return home'* (P7); *'I sort of had to map it out before I went but actually when I started off, I actually really enjoyed it. I went down the river for a bit and then I went up into XX and it was lovely, really exhilarating'* (P14)

(*Continued*)

TABLE 3 Continued

COM-B construct	TDF domain (frequency count)	Sub-themes (frequency count) (Barrier or facilitator)	Example quote
	n. Reinforcement (25)	**i. Habituation of e-cycling** (17) (F)	*Certainly, in terms of taking it to work, yes. It was a case of it was a no-brainer. There would be no reason that I wouldn't take the bike.* (P11): *'No, I wouldn't say I got into the habit of riding it on a daily basis. I wish I did, but I just rode it whenever I could. But certainly, I think it's a habit I could get into'* (P7)
		ii. Sense of achievement (8) (F)	*It makes you feel yourself, makes you feel better in yourself when you actually achieve what you set out to do* (P1)

The bold text here denotes the interviewee speaking.

For those with limited confidence riding on roads, not having easy access to segregated paths negatively impacted their e-cycling. For participants with high levels of confidence riding on the road the absence of cycling infrastructure, while not enjoyable, did not stop them from engaging in that specific ride. There was concern regarding the volume of traffic on cycle paths and the complications of mixing cyclists and pedestrians due to travelling at variable speeds. In addition, a few participants reported that in the dark the cycle paths felt isolated, and they felt vulnerable (Table 3.3.e.i).

Time and weather constraints. Work and personal caring responsibilities inhibited e-cycling for some participants, particularly those in full-time employment who felt they had limited time (Table 3.3.e.vi). Heavy rain and darkness were the two weather related barriers frequently reported by participants (Table 3.3.e.iv). For some participants having wet weather gear and good lights helped to overcome these issues, while others actively chose not to cycle in these conditions despite access to equipment.

E-bike specific issues. The weight of the e-bike was noticeable to all participants and in some cases made the e-bike hard to manoeuvre (Table 3.3.e.ii). In addition, for some the e-bike frame was perceived as being too large, leading to feelings of discomfort. Many participants, potentially due to the weight of the bike, wanted to be able to comfortably put their feet on the ground when stationary. Issues with the perceived size and weight of the frame impacted participants confidence both riding the e-bike and riding on the road. In addition, participants found the battery itself to be inconvenient and heavy to carry around.

Several participants commented that they would like to continue cycling after the trial but that the cost of the bike meant they were unable to do so. For some participants this meant changing to conventional cycling, while for others this meant not engaging in cycling until they had saved sufficient money to purchase an e-bike (Table 3.3.e.iii).

Personal health issues. During the study personal health issues impacted cycling for several participants. These were both acute and chronic in nature. The chronic conditions occurred in participants over 60-years of age, while acute conditions occurred in younger participants. Four participants reported having pre-existing additional health conditions. For two participants this negatively impacted riding (arthritis in hand and difficulty lifting their arm to signal due to cancer treatment) while the other two were able to develop strategies to deal with the health condition (blind in one eye and hearing loss in one ear) (Table 3.3.g.v).

Social opportunity

When instructors were perceived as engaged in the training, participants reported feeling practically and emotionally supported. These instructors delivered more training sessions and participants felt that they practiced riding in areas that they may not have previously considered. However, instructors perceived as being disengaged conducted less training sessions and participants did not feel supported through the training (Table 3.4.f.i/ii).

Outside of the e-bike training, the amount of practical support received and/or desired ranged greatly between participants. Participants with no previous cycling experience desired more practical support to enable or motivate them to ride than those who knew how to cycle (Table 3.4.f.i). Several participants reported cycling with friends and family which was enjoyable and motivational (Table 3.4.f.i). There appeared to be a gender difference with men being content to cycle alone and women desiring greater practical riding support.

Similarly, some participants found verbal support to be encouraging, while others felt their decision to ride was not influenced by others. For individuals who were unsure about whether e-cycling was appropriate for them the feedback from others was impactful, either encouraging them to continue e-cycling or confirming their decision to stop. For one participant, who was struggling with e-cycling, the feedback from their friends impacted their decision to stop riding (Table 3.4.f.ii). There were no apparent differences in the perception of verbal support based on gender.

3.2.3. Motivation

Reflective motivation

Optimism. Participants primary motivation for signing up for the study and engaging in e-cycling was to have a positive impact on their health rather than due to environmental concerns (Table 3.5.g.i). Given their knowledge of the benefits of PA, participants reported being optimistic that e-cycling would positively impact their health (Table 3.5.g.i).

Belief about capabilities. For the majority of participants the e-bike training positively impacted their perceived competence to ride the e-bike and over time, with increased practice, this confidence grew (Table 3.5.g.ii). Participants with recent cycling experience (two to three years) were more confident riding an e-bike on roads and in traffic compared to those that hadn't ridden for a while

(Table 3.5.g.i). However, for some participants, even previous cyclists, the unanticipated differences between conventional cycling and e-cycling, as well as the poor conditions of the road negatively impacted their riding confidence (Table 3.5.g.i).

The weight and size of the e-bike negatively impacted confidence riding the e-bike for some participants (Table 3.5.g.ii). Participants reported how the instructors made a series of alterations to the seat height or provided a smaller size e-bike to increase their comfort and ability to ride. With practice, and alterations to the equipment, participants' felt they were able to ride the bike and became more confident (Table 3.5.g.i/ii).

Overall participants' degree of confidence riding the e-bike impacted their confidence riding on the road. Specifically, participants who were more confident riding the e-bike were also more confident riding on the road with traffic. While those who were uncomfortable on the e-bike reported greater anxiety riding on the roads due to not being able to respond to changing situations and interactions with cars.

Belief about consequences. Beliefs about the consequences of engaging in e-cycling were the most commonly reported facilitators to engagement. Specifically, both men and women felt that e-cycling positively impacted a variety of health outcomes including a) diabetes management, through notable decreases in blood sugar levels, b) improved mental health and c) increased fitness (Table 3.5.i.iii). By comparison, few participants felt that e-cycling had significant financial or environmental implications for themselves.

One of the most commonly reported facilitators to e-cycling was the electrical assistance which enabled participants to travel further, faster and on hillier terrain in comparison to a conventional bicycle (Table 3.5.i.i). This contributed to e-cycling engagement and enabled participants to try out routes that they would not have considered tackling on a conventional bicycle.

Social identity. Using an e-bike regularly for three months enabled some participants to feel more like a cyclist. However, the degree to which participants identified as a cyclist varied greatly. Specifically, participants who reported a stronger e-cycling habit, and greater distances travelled, saw themselves more as cyclists than those who did not get in the habit of cycling regularly and travelled less distance (Table 3.5.j.i). Three participants shared how they would advocate e-cycling to others, while another three reported having specific discussions around the benefits of e-cycling and saw themselves as role models for e-cycling (Table 3.5.j.ii).

Goals. Participants who rode a greater distance over the trial period discussed setting a range of e-cycling goals including riding to a certain location, using less assistance or completing a route in a faster time (Table 3.5.k.i).

Intentions. Prior to the study participants planned to use the e-bike for both recreational and utilitarian purposes. However, for those that intended to make utilitarian journeys via e-bike, and replace other transport modes, they discussed how they were unable to achieve this intention due to a range of environmental barriers identified above (Table 3.5.l.ii). Though one participant, who planned to use the e-bike purely for leisure, used it primarily for commuting (Table 3.5.l.ii). This individual felt able to commute on the e-bike due to access to safe parking infrastructure at their place of work.

At the end of the study, 12 participants wanted to continue riding an e-bike, with five actively seeking out e-bike purchasing options and one purchasing an e-bike part way through the study (Table 3.5.l.i). Two participants wanted to continue riding on a conventional bicycle following the study. Of those seeking out e-bikes half reported that an e-bike was out of their price range and expressed a need to save up or wait for a change of circumstances (e.g., retirement).

Automatic motivation

Emotion. The enjoyment associated with e-cycling was a key facilitator to engagement. Specifically, the ability to ride new and longer routes meant e-cycling led to feelings of enjoyment (Table 3.6.m.i). Part of the enjoyment of e-cycling came from being in the fresh air and nature and having the ability to explore new routes. Cyclically, the enjoyment associated with riding led participants to ride further and more frequently than they had anticipated.

Reinforcement. Participants reported experiencing a sense of achievement once a ride was complete (Table 3.6.n.ii). This achievement, along with the enjoyment, led to increased riding and some participants commented how this helped e-cycling to become a habit for them (Table 3.6.n.i).

4. Discussion

This theory-based qualitative study examined the factors associated with engagement in e-cycling among individuals with type 2 diabetes, with a particular focus on identifying barriers and facilitators to engagement. In addition, the study sought to develop a conceptual understanding of how these factors relate to one another to impact behaviour. This information can be used to refine the current intervention (57) and/or guide future initiatives aimed at increasing e-cycling in people living with chronic disease. The key findings of this study are discussed below.

4.1. The importance of e-bike training to build actual and perceived capability

The results of this study highlight that regardless of previous cycling experience e-bike training is beneficial, providing participants with riding skills, knowledge of how to safely ride on roads and where and how to access segregated cycling infrastructure. Consequently, participants reported increased confidence when riding the e-bike, riding on the road and exploring new cycling routes. The increase in confidence was greatest among individuals who had not cycled for a considerable period of time. Similar increases in confidence have been reported among older adults in the UK following e-bike training (58). Furthermore, a recent review of conventional bike skills training programmes concluded that training led to increased riding confidence, and was positively associated with increased cycling frequency (29). These findings highlight the importance of training to target key individual level predictors of e-cycling, namely skills, knowledge, and confidence.

Despite the apparent positive impact of training on cycling behaviour, e-bike interventions rarely report the details of training provided. This maybe because no formal training is conducted, training is minimal, or researchers do not consider the impact of the e-bike training on behaviour. Lack of reporting of intervention content and duration is a similar problem in conventional cycling studies (29). An understanding of what is delivered as part of an e-cycling intervention is important to determine what is most likely to facilitate e-cycling. E-bike training is of particular importance to older adults or people living with chronic disease who may have pre-existing health concerns that require adaptations to the e-bike, riding style or riding location. These issues can be addressed and overcome with support from an instructor, as was the case in the current trial. It is important to note that in the current trial three participants, (two with a little cycling experience and one with no experience) required more than the specified four training sessions, highlighting the need to tailor e-bike training.

In addition, more support was desired for women who had less cycling experience than men when entering the study, a finding echoed in other e-bike trials (59). In the current trial men completed higher levels of skills training (National Cycling Skills levels two and three) than women prior to taking the e-bike home and cycled further, on average, than women during the trial. Previous cycling research has shown that higher levels of national skills cycle training completed is associated with more riding (60). As such, women should be supported to reach these higher levels of skills training prior to an e-bike loan.

Instructor led cycling sessions conducted during the e-bike loan made participants feel supported and offered an informal setting in which to discuss e-cycling and practice riding. Furthermore, participants that attended these sessions rode further than those that did not. Serali and colleagues (29) found that cycling frequency decreased over time following training and recommend that training should be followed up by post training support to ensure that participants consolidate the skills and confidence gained during training. This recommendation is supported by the findings of the current study and suggest that the additional support provided in the current study, above and beyond delivering skills training, is important to practice skills and maintain confidence. Conversely, when participants reported instructors to be disengaged in the training this negatively impacted confidence. As such, instructors need to be comprehensively trained, not only on the skills component, for which they were confident (49), but also on how to offer support and effectively engage with a population who may require more support than the instructors are used to providing.

4.2. E-bike size and weight concerns

Despite comprehensive training several participants reported that the e-bike was too large making it difficult to manoeuvre, leading to decreased confidence riding the e-bike in general and in traffic. While the e-bikes provided were an appropriate size based on participants' height, participants wanted to be able to fully place their feet on the ground. E-bike size concerns are not a commonly reported barrier to e-cycling and could be due to the characteristics of this sample. Specifically, the current sample were classified as obese and had extremely low fitness levels which could have negatively impacted balance (49). In addition, a type 2 diabetes diagnosis is associated with reduced balance (61–63). This reduced balance and low fitness could have meant participants found it hard to manage the weight of the e-bike when stopping and starting. In the current study the provision of a smaller frame size, which enabled the participant to fully plant their feet on the ground, was associated with increased confidence riding the e-bike and riding on roads. As such, the provision of smaller e-bike frames than is standard would likely increase riding confidence and engagement in e-cycling in this population.

4.3. Motivational factors that impact e-cycling

Participants were motivated to engage in e-cycling to improve their health as opposed to impacting the environment. This optimism regarding health was largely met, with participants perceiving improvements in fitness, mental health and diabetes management, findings echoed in previous e-cycling research (42). Engaging in e-cycling was perceived as an easier way of managing their diabetes than diet or other types of exercise, largely due to the enjoyment of riding. Enjoyment came from the ability to ride a bike comfortably due to less physical exertion than a conventional bicycle and the ability to ride further, faster and on hillier terrain than previously possible. These benefits are consistently reported in the e-cycling literature (34). A substantive body of literature now demonstrates that positive enjoyment during exercise is associated with greater future engagement (64) and is a unique aspect of e-cycling over other forms of active travel. High levels of enjoyment appeared to increase the habit of e-cycling in the current sample, with participants who felt e-cycling had become habit accumulating greater kilometres ridden than those who did not.

4.4. The need for social support

In the current sample, the degree to which support was required, or desired, varied based on level of experience and gender. Specifically, individuals with low levels of cycling experience, who were primarily women, required and desired more practical support from both the instructor and friends and family. One participant attributed their inability to become an independent cyclist on a lack of social support in their personal life. In addition, women reported wanting to ride with friends or family to a greater extent than men. Conversely, men reported that e-cycling alone was relaxing and enjoyable. This has been reported in other e-cycling studies among older adults (58, 65). In the current study verbal support was less influential than practical support. This may be due to the higher-than-average rates of cycling in Bristol and potentially a community acceptance of cycling in general (66).

4.5. The impact of the natural and built environment

Access to safe parking infrastructure was a commonly reported barrier to utility e-cycling. Specifically, a lack of safe parking facilities and fear of theft negatively impacted riding. While these are commonly reported barriers to cycling (34, 67) these fears were exacerbated in the current study due to the e-bike not being owned by the participant and concerns over the financial implications of e-bike theft. While there is scant evidence of the impact of bicycle parking in cities on cycling behaviour, Heinen and colleagues report that the supply and quality of parking can impact cycling behaviour (68).

Home parking facilities were also a concern for some participants. Specifically, participants reported having to park the e-bike in the house and the effort required to get the bike in and out negatively impacted riding. Very little research has explored the impact of home parking facilities on cycling behaviour. This concern maybe more pertinent to e-bikes which are heavier and bulkier than conventional bicycles (69). In the current study two participants reported regularly commuting to work. These individuals reported having access to safe bicycle storage and showers and in one case the company had restricted car parking making e-cycling more attractive. Workplace facilities and polices such as these have been found to be positively associated with cycle commuting (70–73).

The cycling infrastructure to which an individual had access also impact riding. Specifically, participants were more willing to cycle when they had access to a segregated cycling path close to their home. Providing infrastructure that supports the needs of cyclists is recognised as a key strategy to encourage more cycling in cities (74–76). Two recent systematic reviews show that cycling behaviour increased following the introduction of new infrastructure or upgrading existing infrastructure (77, 78), however evaluation of environmental interventions is complex and findings vary based on the method of evaluation used (79).

Overall factors associated with the natural and built environment were instrumental in participants decision to engage in e-cycling or take an alternative mode of transport. In some cases, participants removed any notion of utility cycling and stuck to recreational rides due to these barriers, this was particularly relevant for individuals with no or little previous riding experience. While participants were encouraged to engage in problem solving and action planning to overcome such barriers, the extent to which individuals engaged in these activities at appropriate times is unknown.

4.6. The financial cost of e-bikes

Trialling an e-bike led to 12 of the 16 participants wanting to purchase an e-bike to continue riding, largely due to the high level of enjoyment. This is in line with other research which has reported that the desire to purchase an e-bike substantially increases following a e-bike trial and is associated with enjoyment, positive attitudes towards e-bikes and perceived benefits (59, 80). While many individuals are willing to pay the large expense of an e-bike (59, 80, 81) others, including individuals in this study, although willing, do not have the financial security to be able to purchase an e-bike (59). Following completion of a trial period, purchasing an e-bike has been reported to be an independent predictor of e-bike use over time (59) and is associated with reducing an individual's habitual use of the car (82). As such, ways of helping participants to view e-bikes as a financially viable option is of upmost importance.

4.7. Strengths and limitations

A strength of this research is the use of the TDF and COM-B to examine experiences of e-cycling in this population. To the authors' knowledge this is the first time this framework and model have been used to explore peoples understanding and perception of e-cycling. Their use allow for the exploration of factors beyond skills and knowledge-based considerations and for the development of an understanding of the impact of context on e-cycling engagement. This information can be used to develop a programme theory, identifying hypothesised causal pathways, which can be tested in future trials. However, there are several limitations. Firstly, using the thematic approach means that data are combined and summarised, so that individual level detail maybe lost (83). In the current analysis the aim was to bring forward unique cases into the matrix and report these in the results. Secondly, thematic analysis focuses primarily on what the data show, thus failing to consider potential areas that are not discussed. While this is hard to avoid, use of the TDF ensured that a wide range of topics were covered. Thirdly, telephone interviews have been suggested to be inferior to face-to-face interviews due to a lack of visual cues, however, there is limited evidence to support this statement (84). Rather, telephone interviews may enable participants to share information more openly than face-to-face interviews, and participants maybe more relaxed when talking from the comfort of their own home (84). Fourthly, the role of the researcher may have impacted the data obtained, the analysis and the findings. The prior relationship that the researcher, who conducted the pilot RCT, had with participants may have impacted how participants responded to questions. To try and overcome this a distinction was made between the e-bike training and the study, to help the participant view them as different components to encourage honest opinions to be shared. Participants were asked to give frank answers to enable intervention improvements. In addition, the researchers who conducted the analysis were commuting cyclists at the time of the study. This may have influenced interpretation of the data. However, interpretations made by the researchers and reviewed by the participants showed consistency, therefore increasing the trustworthiness of the findings. Fifthly, 94% of the sample identified as White. As such, these findings cannot be generalised to other ethnicities. However, a strength of the study is the equal inclusion of men and women. Sixthly, 14 of the 16 participants had some degree of cycling experience, which may bias the identified barriers and facilitators to e-cycling reported and therefore the current findings cannot be generalised to individuals new to cycling. Individuals who had recent cycling experience (i.e., in the last two or three years) had greater perceived capability and confidence than those with little or no cycling experience. While one individual who had never previously cycled was unable to e-cycle following instruction. However, the degree to which previous cycling experience impacted current e-cycling behaviour depended largely on the individual and additional contextual factors.

4.8. Implications for future research

Using the information obtained from this analysis, researchers should refine the intervention to address some of the highlighted concerns using the Behaviour Change Wheel. Following refinement, a programme theory should be developed to generate hypotheses about how the intervention impacts cycling in this population. This can be used to guide the selection of quantitative mechanistic outcomes and contextual variables that should be examined in a future trial. Further research should be conducted to differentially examine the impact of such e-cycling interventions on individuals new to cycling or who have not ridden for a considerable amount of time, as the degree of training required appears to be different to those who are confident with cycling. In addition, such an intervention should be trialled in different populations to allow comparison of experiences.

While training is important, it needs to be part of a multifaceted approach including improving infrastructure and introducing policy to encourage e-cycling engagement. Future research should involve working with stakeholders to establish how to address some of the contextual barriers to e-cycling, specifically cycling and parking infrastructure and traffic concerns, and the impact that addressing these components has on e-cycling engagement. In addition, means through which to address the financial cost of initiating e-cycling should be explored. Examining the relative impact of these micro-environmental, social and individual factors, and their associated costs, will provide guidance on how best to promote e-cycling in the future and highlight the potential for scalability.

5. Conclusion

Findings from this study provide insight into the personal, social and environmental factors that individuals with type 2 diabetes report as barriers and facilitators to e-cycling. Using the TDF and COM-B model is a starting point to understanding e-cycling in the current context and identifying what needs to change to modify the behaviour. This can inform the development of a conceptual framework which hypothesizes how these factors impact one another to influence e-cycling behaviour. This is the first step in developing an understanding of the mechanisms through which the e-bike training impacts individual capability and motivation, and identifying the importance of different environmental and social factors on e-cycling engagement. The findings of this study can be used to improve the quality of bicycle skills training currently being offered and to guide the selection of mechanistic outcome measures for future evaluation, guide scale-up to other locations and inform policymakers of what further actions need to be taken to enable people to adopt bicycling.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by NHS Health Research Authority Southwest/Central Bristol Research Ethics Committee (Ref: 18/SW/0164). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

JB designed the study. SL, CE and AS contributed to the design of the study. JB collected the data. JB and AS analysed the data. JB drafted the full manuscript. All authors contributed to the article and approved the submitted version.

Funding

This study was funded by the NIHR Biomedical Research Centre at University Hospitals Bristol and Weston NHS Foundation Trust and the University of Bristol. The views expressed are those of the authors and not necessarily those of the NIHR or the Department of Health and Social Care.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fspor.2023.1150724/full#supplementary-material

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