DSX 18 (2024) 102995

Contents lists available at ScienceDirect

Diabetes & Metabolic Syndrome: Clinical Research & Reviews

journal homepage: www.elsevier.com/locate/dsx

Explanatory variables of objectively measured 24-h movement behaviors in people with prediabetes and type 2 diabetes: A systematic review

Lotte Bogaert [a,1], Iris Willems [a,b,1], Patrick Calders [a], Eveline Dirinck [c], Manon Kinaupenne [a], Marga Decraene [a,d], Bruno Lapauw [e], Boyd Strumane [f], Margot Van Daele [f], Vera Verbestel [g,h,2], Marieke De Craemer [a,2,*]

[a] Ghent University, Department of Rehabilitation Sciences, Ghent, Belgium
[b] Research Foundation Flanders, Brussels, Belgium
[c] Department of Endocrinology, Antwerp University Hospital & University of Antwerp, Antwerp, Belgium
[d] Ghent University, Department of Movement and Sports Sciences, Ghent, Belgium
[e] Department of Endocrinology & Department of Internal Medicine and Pediatrics, Ghent University Hospital & Ghent University, Ghent, Belgium
[f] Faculty of Medicine and Health Sciences, Ghent, Belgium
[g] Faculty of Health, Medicine and Life Sciences, Department of Health Promotion, Research Institute of Nutrition and Translational Research in Metabolism (NUTRIM), Maastricht University, the Netherlands
[h] Faculty of Health, Medicine and Life Sciences, Department of Health Promotion, Care and Public Health Research Institute (CAPHRI), Maastricht University, the Netherlands

ARTICLE INFO

Keywords:
Type 2 diabetes
Prediabetes
24-h movement behaviors
Physical activity
Sedentary behavior
Sleep
Explanatory variables

ABSTRACT

Aim: Physical activity (PA), sedentary behavior (SB) and sleep (i.e. 24-h movement behaviors) are associated with health indicators in people with prediabetes and type 2 diabetes (T2D). To optimize 24-h movement behaviors, it is crucial to identify explanatory variables related to these behaviors. This review aimed to summarize the explanatory variables of 24-h movement behaviors in people with prediabetes or T2D.
Methods: A systematic search of four databases (PubMed, Web of Science, Scopus & Embase) was performed. Only objective measurements of 24-h movement behaviors were included in the search strategy. The explanatory variables were classified according to the levels of the socio-ecological model (i.e. intrapersonal, interpersonal and environmental). The risk of bias was assessed using the Joanna Briggs Institute appraisal checklist.
Results: None of the 78 included studies investigated 24-h movement behaviors. The majority of the studies investigated PA in isolation. Most studied explanatory variables were situated at the intrapersonal level. Being male was associated with more moderate to vigorous PA but less light PA in people with T2D, and more total PA in people with prediabetes. An older age was associated with a decrease in all levels of PA in people with T2D. HbA1c was positively associated with sleep and SB in both groups. No associations were found at the interpersonal or environmental level.
Conclusion: The results of this review underscore the lack of a socio-ecological approach toward explanatory variables of 24-h movement behaviors and the lack of focus on an integrated 24-h movement behavior approach in both populations.

* Corresponding author.
E-mail addresses: Lotte.Bogaert@ugent.be (L. Bogaert), Willems.Iris@ugent.be (I. Willems), Patrick.Calders@ugent.be (P. Calders), eveline.dirinck@uza.be (E. Dirinck), Manon.Kinaupenne@UGent.be (M. Kinaupenne), Marga.Decraene@UGent.be (M. Decraene), Bruno.Lapauw@uzgent.be (B. Lapauw), Boyd.Strumane@ugent.be (B. Strumane), Margovda.Vandaele@ugent.be (M. Van Daele), vera.verbestel@maastrichtuniversity.nl (V. Verbestel), Marieke.Decraemer@ugent.be (M. De Craemer).
[1] Lotte Bogaert and Iris Willems joint first author.
[2] Marieke De Craemer and Vera Verbestel joint last author.

https://doi.org/10.1016/j.dsx.2024.102995

Available online 1 April 2024
1871-4021/

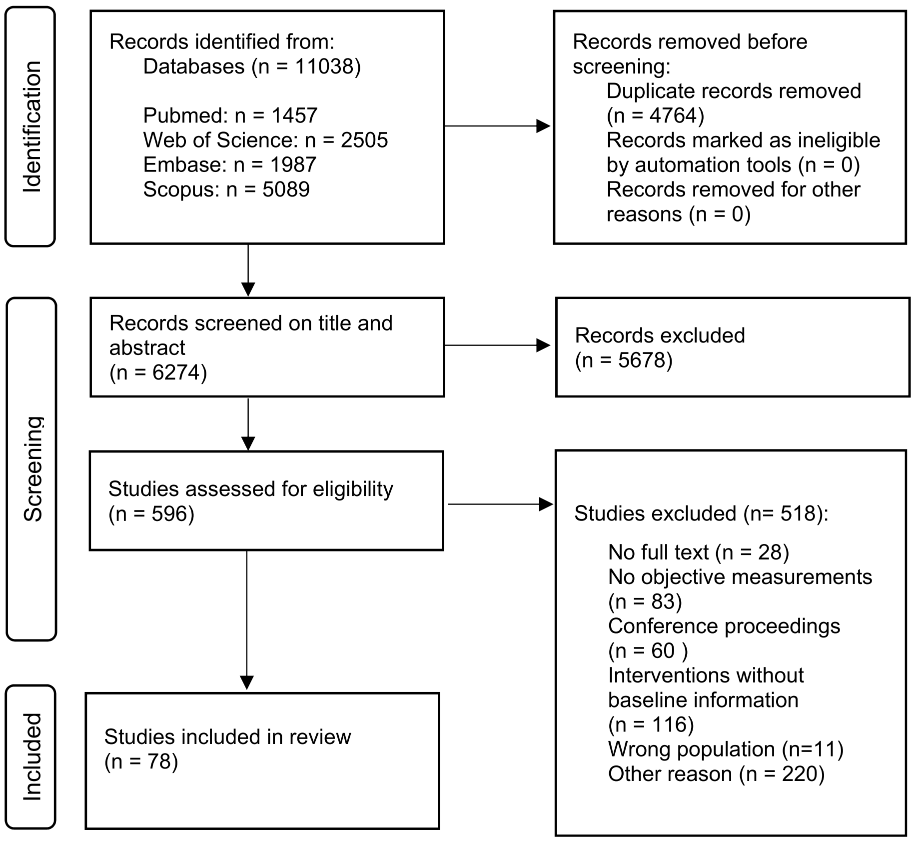

Fig. 1. Preferred reporting items for systematic reviews and meta-analyses flowchart of the systematic literature search.

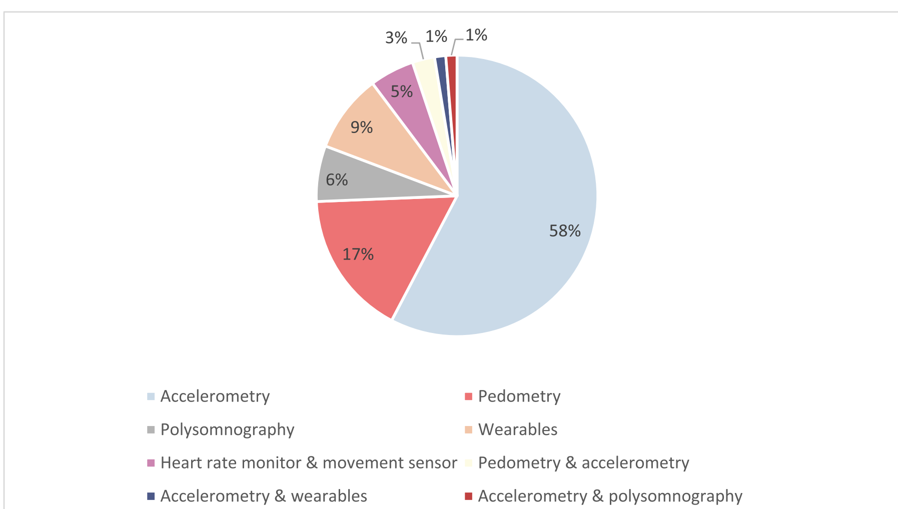

Fig. 2. Objective measurement methods of included studies.

1. Introduction

Prediabetes is a health condition characterized by a blood glucose level higher than the normal level (fasting glucose: 100–125 mg/dl) and falling below the diagnostic threshold of diabetes (fasting glucose: ≥126 mg/dl) [1,2]. Moreover, prediabetes represents a significant risk factor for the onset of type 2 diabetes (T2D) as a quarter of people with prediabetes develop T2D within five years after diagnosis and 70% develop T2D during their lifetime [2]. Both diseases are associated with numerous complications (e.g. cardiovascular disease) resulting in increased mortality [3,4]. In 2021, the International Diabetes Federation registered 573 million people with diabetes worldwide, of which 90% had T2D. This number is expected to increase to 783 million by 2045, revealing the rapidly increasing global burden of this disease [5].

Adequate disease management is necessary to prevent or delay the progression from prediabetes to T2D and, in people with T2D, to obtain an optimal glycemic control and prevent diabetes-related complications [6–9]. An important aspect of disease management involves a healthy lifestyle wherein the allocation of time to physical activity (PA), sedentary behavior (SB) and sleep throughout a 24-h day (i.e. 24-h movement behaviors) is known to be associated with favorable health

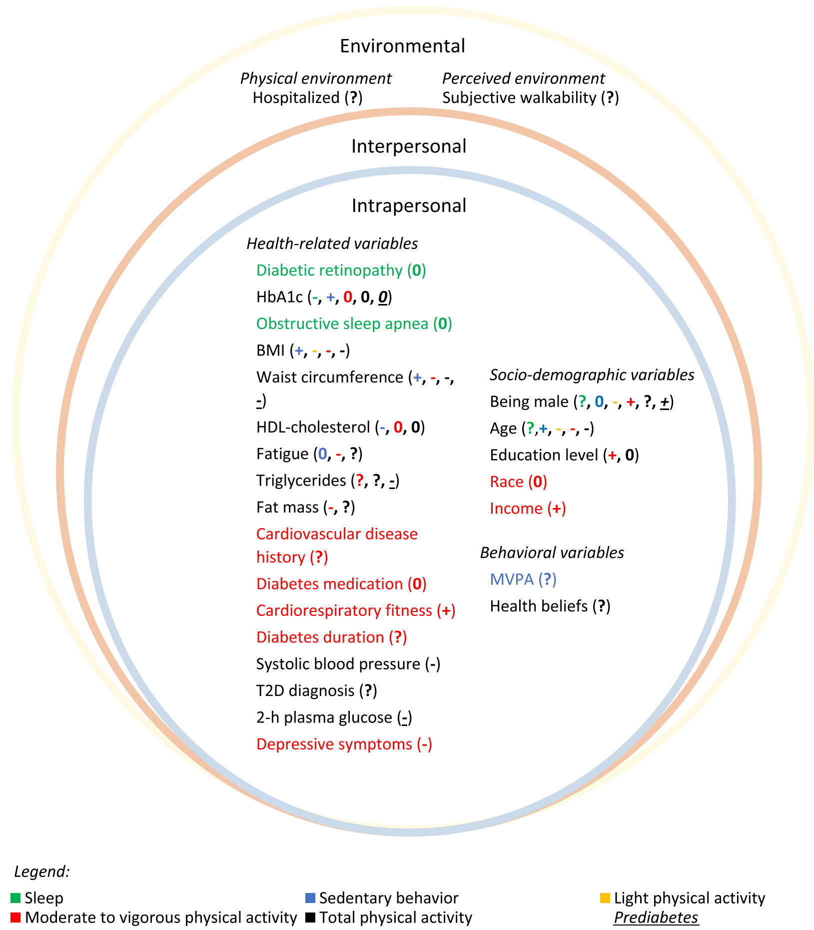

Fig. 3. Explanatory variables of PA, SB and sleep in people with T2D and people with prediabetes classified according to three domains of the socio-ecological model. *Abbreviations*: PA, Physical activity; SB, Sedentary behavior, T2D, type 2 diabetes mellitus; BMI, body mass index; HDL-cholesterol, high-density lipoprotein cholesterol; T2D, type 2 diabetes; MVPA, moderate to vigorous physical activity; LPA, light physical activity; total PA, total physical activity.

Table 1
Explanatory variables of sleep duration in people with prediabetes and direction and strength of association.

	Related to sleep duration		Unrelated to sleep duration	Summary code[a]		Strength of conclusion[d]
	Positive association	Negative association		n/N for row (%)[b]	Association (+/−/0/?)[c]	
Intrapersonal variables						
Socio-demographic variables						
Not reported						
Health-related variables						
Obstructive sleep apnea		Mokhlesi et al., 2021 [102]		1/1 (100%)	–	4
HbA1c		Reutrakul et al., 2018 [29]		1/1 (100%)	–	4
Behavioral variables						
Not reported						
Interpersonal variables						
Not reported						
Environmental variables						
Physical environmental variables						
Not reported						
Perceived environmental variables						
Not reported						

Abbreviations: HbA1c, hemoglobin A1c.
[a] Summary code is an overall summary of the findings for each variable separately.
[b] n = Number of studies that report support for the direction of the association; N = number of studies that have investigated and reported on possible associations between the variable and sleep duration.
[c] Shows the direction of the individual/summary association.
[d] Based on the Evidence-Base Guideline Development method (Meeus et al. [33]).

Table 2
Explanatory variables of SB in people with prediabetes and direction and strength of association.

	Related to SB		Unrelated to SB	Summary code[a]		Strength of conclusion[d]
	Positive association	Negative association		n/N for row (%)[b]	Association (+/−/0/?)[c]	
Intrapersonal variables						
Socio-demographic variables						
Age	Rockette-Wagner et al., 2017 [103]			1/1 (100%)	+	4
Health-related variables						
Waist circumference	Swindell et al., 2018 [31]			1/1 (100%)	+	4
Systolic blood pressure	Swindell et al., 2018 [31]			1/1 (100%)	+	4
Diastolic blood pressure	Swindell et al., 2018 [31]			1/1 (100%)	+	4
Fasting insulin	Swindell et al., 2018 [31]			1/1 (100%)	+	4
Fasting glucose			Swindell et al., 2018 [31]	0/1 (0%)	0	4
2-h plasma glucose	Swindell et al., 2018 [31]			1/1 (100%)	+	4
HbA1c			Swindell et al., 2018 [31]	0/1 (0%)	0	4
HOMA-IR	Swindell et al., 2018 [31]			1/1 (100%)	+	4
Triglycerides	Swindell *et al.* 2018 [31]			1/1 (100%)	+	4
Total cholesterol			Swindell et al., 2018 [31]	0/1 (0%)	0	4
HDL-cholesterol		Swindell et al., 2018 [31]		1/1 (100%)	–	4
LDL-cholesterol			Swindell et al., 2018 [31]	0/1 (0%)	0	4
CRP	Swindell et al., 2018 [31]			1/1 (100%)	+	4
Neck pain			Dzakpasu et al., 2023 [104]	0/1 (0%)	0	4
Shoulder pain			Dzakpasu et al., 2023 [104]	0/1 (0%)	0	4
Low back pain			Dzakpasu et al., 2023 [104]	0/1 (0%)	0	4
Knee pain			Dzakpasu et al., 2023 [104]	0/1 (0%)	0	4
Behavioral variables						
Not reported						
Interpersonal variables						
Not reported						
Environmental variables						
Physical environmental variables						
Not reported						
Perceived environmental variables						
Not reported						

Abbreviations: SB, sedentary behavior; HbA1c, Hemoglobine A1c; HOMA-IR, homeostatic model assessment of insulin resistance; HDL-cholesterol, high-density lipoprotein cholesterol; LDL-cholesterol, low-density lipoprotein cholesterol; CRP, c-reactive protein.

[a] Summary code is an overall summary of the findings for each variable separately.

[b] n = Number of studies that report support for the direction of the association; N = number of studies that have investigated and reported on possible associations between the variable and sedentary behavior.

[c] Shows the direction of the individual/summary association.

[d] Based on the Evidence-Base Guideline Development method (Meeus et al. [33]).

outcomes [10]. Research among people with prediabetes and T2D has shown that even limited time reallocations (5–30 min) from SB to light physical activity (LPA) or moderate physical activity (MVPA) have beneficial effects on health indicators such as adiposity and insulin resistance [11–13].

To enhance 24-h movement behaviors, it is essential to investigate the various factors influencing these behaviors. Comprehending all explanatory variables is complex due to their interconnections across diverse socio-ecological levels, including personal, social and environmental dimensions. Notably, factors such as sex (interpersonal), social support (interpersonal) and neighborhood walkability (environment) are associated with the time spent in PA in adults with T2D [14,15]. Given the range of variables involved in explaining behavior, it is imperative to identify explanatory variables associated with 24-h movement behaviors across all socio-ecological levels. The most complete and widely-used model to summarize explanatory variables is the socio-ecological model (SEM) of Sallis et al. [9] which includes the 1) the intrapersonal level (subdivided into socio-demographic (e.g. age, sex), behavioral (e.g. attitude, beliefs) and health-related variables (e.g. comorbidities, quality of life)), 2) the interpersonal level (e.g. modelling, social support), 3) the environmental level (subdivided into the physical environment (e.g. proximity of green spaces, parks, shops and public transport, presence of sidewalks) and the perceived environment (e.g. neighborhood satisfaction, sense of safety, aesthetics, perception of accessibility and availability of sidewalks and bike lanes)) and 4) the policy level (e.g. laws, rules, education and employment opportunities). Recognizing that behaviors are influenced by multiple levels, this multilevel model stands out as the most comprehensive framework for understanding explanatory variables [16–18]. Furthermore, the Ottawa Charter for Health Promotion recommends this multilevel socio-ecological approach, recognizing it as an effective strategy for promoting behavioral change [19,20].

To the best of our knowledge, there is no systematic review summarizing the evidence on the explanatory variables of 24-h movement

Table 3
Explanatory variables of LPA in people with prediabetes and direction and strength of association.

	Related to LPA		Unrelated to LPA	Summary code[a]		Strength of conclusion[d]
	Positive association	Negative association		n/N for row (%)[b]	Association (+/−/0/?)[c]	
Intrapersonal variables						
Socio-demographic variables						
Sex (being male)		Rockette-Wagner et al., 2017 [103]		1/1 (100%)	–	4
Age		Rockette-Wagner et al., 2017 [103]		1/1 (100%)	–	4
Health-related variables						
Not reported						
Behavioral variables						
Not reported						
Interpersonal variables						
Not reported						
Environmental variables						
Physical environmental variables						
Not reported						
Perceived environmental variables						
Not reported						

Abbreviations: LPA, light physical activity.
[a] Summary code is an overall summary of the findings for each variable separately.
[b] n = Number of studies that report support for the direction of the association; N = number of studies that have investigated and reported on possible associations between the variable and LPA.
[c] Shows the direction of the individual/summary association.
[d] Based on the Evidence-Base Guideline Development method (Meeus et al. [33]).

behaviors in people with prediabetes or T2D. Therefore, the aim of this systematic review was to identify the explanatory variables of 24-h movement behaviors, summarized within the SEM, in both populations. The results of this manuscript will provide recommendations for the development of future interventions targeting 24-h movement behaviors in people with prediabetes and T2D.

2. Methods

The Preferred Reporting Items for Systematic reviews and Meta-Analyses guidelines [21] were applied in conducting this systematic review. The protocol was registered on PROSPERO (ID: CRD42021251898).

2.1. Search strategy

The literature was searched systematically for articles related to explanatory variables of 24-h movement behaviors in people with prediabetes or T2D. To limit findings based on recall bias and over- or underestimation due to self-reports, only objectively measured 24-h movement behaviors were included. The research question was formulated using the Population – Intervention – Outcome approach: "What are the explanatory variables (O) of objectively measured 24-h movement behaviors (I) in people with prediabetes or people with T2D (P)?"

To answer this research question, three key concepts were used: pathology (prediabetes, T2D), objective measurement, and movement behaviors. These key concepts were linked via the Boolean operator 'AND'.

Four electronic databases (i.e. MEDLINE (PubMed), Embase, Scopus and Web of Science) were searched (last search 22/09/2023). The search strategy for every database can be found in Supplementary file 1.

2.2. Eligibility criteria

Rayyan (http://rayyan.qcri.org) was used as an electronic library to manage the references from the final search strategy. First, duplicates were removed after which the title and abstract were screened by three independent reviewers (IW, MD, MK). In case of discrepancies, a fourth reviewer (MDC) was asked to adjudicate the results. Full text screening was conducted by six independent reviewers (LB, IW, VV, BS, MVD, MDC). If the full text was unavailable, the corresponding author was contacted and authors were asked to send the full text.

Screening was based on inclusion and exclusion criteria. The inclusion criteria were as follows: (1) adults with prediabetes or T2D, (2) objectively measured PA, SB and/or sleep, (3) assessment of at least one explanatory variable, (4) full text availability and, (5) written in English. Cross-sectional studies, longitudinal-observational studies and baseline measurements of intervention studies were included. The following exclusion criteria were applied: (1) adults with types of diabetes mellitus other than prediabetes or T2D, (2) adults with other internal, metabolic, neurological, physical and/or psychological diseases and, (3) reviews, meta-analyses, letters to authors, conference abstracts and animal studies.

A manual search of the reference lists of the included articles was performed and relevant articles were included in the final selection when the eligibility criteria were met.

2.3. Data extraction

The data were extracted by six independent reviewers (LB, IW, VV, BS, MVD, MDC). Information on the following characteristics was extracted: (1) author and year of publication, (2) country, (3) population (T2D and/or prediabetes), (4) sample size, (5) age in years, (6) sex (% male), (7) study design (8) movement- (i.e. PA, SB and/or sleep), and subbehavior(s) (i.e. LPA, MVPA), (9) measurement method, (10) intrapersonal/interpersonal/environmental explanatory variables, and (11) direction of the association.

Movement behaviors are expressed in different units. The following units were included: total sleep duration (hours/day or minutes/day), SB (hours/day), LPA (hours/day or minutes/day), MVPA (hours/day or minutes/day, (not) achieving 150 min of MVPA per day, weekly MVPA (hours/week or minutes/week), metabolic equivalent of task (MET)/minute, bouts/day, minutes/bout and METs/day)) and total PA (total time (in min/day), steps/day, PA level (total energy expenditure/basal metabolic rate), total energy expenditure (kcal/day), PA energy expenditure (kcal/day or kilojoule/kg/day), steps/day ≥7100 and steps/day <4873). All the explanatory variables were included in the tables even if they were investigated once, however, only the explanatory variables that were investigated in at least two independent studies are mentioned in the Results section.

2.4. Risk of bias

The risk of bias was assessed by two independent reviewers (LB and MDC), using the Joanna Briggs Institute appraisal checklist for analytical cross-sectional studies [22]. This checklist contains eight questions

Table 4
Explanatory variables of MVPA in people with prediabetes and direction and strength of association.

	Related to MVPA		Unrelated to MVPA	Summary code[a]		Strength of conclusion[d]
	Positive association	Negative association		n/N for row (%)[b]	Association (+/−/0/?)[c]	
Intrapersonal variables						
Socio-demographic variables						
Sex (being male)	Rockette-Wagner et al., 2017 [103]			1/1 (100%)	+	4
Age		Rockette-Wagner et al., 2017 [103]		1/1 (100%)	−	4
Health-related variables						
Waist circumference		Swindell et al., 2018 [31]		1/1 (100%)	−	4
Systolic blood pressure			Swindell et al., 2018 [31]	0/1 (0%)	0	4
Diastolic blood pressure			Swindell et al., 2018 [31]	0/1 (0%)	0	4
Fasting insulin		Swindell et al., 2018 [31]		1/1 (100%)	−	4
Fasting glucose			Swindell et al., 2018 [31]	0/1 (0%)	0	4
2-h plasma glucose		Swindell et al., 2018 [31]		1/1 (100%)	−	4
HbA1c		Swindell et al., 2018 [31]		1/1 (100%)	−	4
HOMA-IR		Swindell et al., 2018 [31]		1/1 (100%)	−	4
Triglycerides		Swindell et al., 2018 [31]		1/1 (100%)	−	4
Total cholesterol			Swindell et al., 2018 [31]	0/1 (0%)	0	4
HDL-cholesterol	Swindell et al., 2018 [31]			1/1 (100%)	+	4
LDL-cholesterol			Swindell et al., 2018 [31]	0/1 (0%)	0	4
CRP		Swindell et al., 2018 [31]		1/1 (100%)	−	4
Behavioral variables						
Not reported						
Interpersonal variables						
Not reported						
Environmental variables						
Physical environmental variables						
Neighborhood[e]			Kariuki et al., 2022 [28]	0/1 (0%)	0	3
Perceived envrionmental variables						
Not reported						

Abbreviations: MVPA, moderate to vigorous physical activity; HbA1c, Hemoglobine A1c; HOMA-IR, homeostatic model assessment of insulin resistance; HDL-cholesterol, high-density lipoprotein cholesterol; LDL-cholesterol, low-density lipoprotein cholesterol; CRP, c-reactive protein.
[a] Summary code is an overall summary of the findings for each variable separately.
[b] n = Number of studies that report support for the direction of the association; N = number of studies that have investigated and reported on possible associations between the variable and MVPA.
[c] Shows the direction of the individual/summary association.
[d] Based on the Evidence-Base Guideline Development method (Meeus et al. [33]).
[e] Car-dependent vs walkable neighborhood.

about the inclusion criteria, validity and reliability of the measurements and outcomes, confounding factors and statistical analysis. Possible answers were “yes”, “no”, “unclear” or “not applicable”. The following scoring was applied based on the yes-score: low risk of bias (≥70%), moderate risk of bias (50–69%) and high risk of bias (≤49%).

2.5. Level of evidence and level of conclusion

All included studies were assigned a level of evidence (ranging from A1 to D) by two independent reviewers (LB and MDC) using the Evidence-Base Guideline Development (EBRO) method (Supplementary file 2) [23]. Disagreements in the scores were discussed by the two reviewers (LB and MDC) until a consensus was reached. After that, each investigated explanatory variable was assigned a strength of conclusion (level 1; high strength of conclusion – level 4; low strength of conclusion) by using the EBRO method depending on the level of evidence of the respective studies and the consistency of their results (Supplementary file 2) [23].

2.6. Data synthesis

The explanatory variables of 24-h movement behaviors were classified across three different domains using the SEM [16]: (1) intrapersonal (subdivided into socio-demographic, health-related and behavioral), (2) interpersonal and, (3) environmental (subdivided into physical environment and perceived environment) variables. The policy domain is not mentioned since no studies have investigated variables at this level. In addition, PA was subdivided into total PA, LPA and MVPA. The strength of evidence for the association between an explanatory variable and PA, SB and/or sleep was coded according to the model used by Sallis et al. [24] and Hinkley et al. [25,26] (Supplementary file 3). The percentage of associations in the hypothesized direction was determined by dividing the number of findings supporting the association (e.g. positive association) by the total number of findings in which an association (e.g. positive, negative and no association) was mentioned. For example, if two studies reported a positive association and four studies no association, the final association was coded as “no association” (2/6, 33%).

3. Results

3.1. Study characteristics

The final literature search identified 11,038 references. After excluding 4764 duplicates, 6274 studies were screened for title and abstract, resulting in 596 full texts. A total of 78 studies were ultimately included (Fig. 1). The explanatory variables of sleep, SB or PA were investigated in seven studies

Table 5
Explanatory variables of total PA in people with prediabetes and direction and strength of association.

	Related to total PA		Unrelated to total PA	Summary code[b]		Strength of conclusion[e]
	Positive association	Negative association		n/N for row (%)[c]	Association (+/−/0/?)[d]	
Intrapersonal variables						
Socio-demographic variables						
Age		Chasens et al., 2012		1/1 (100%)	−	4
Sex (being male)	Chasens et al., 2012 [27] Steeves et al., 2015 [30]		Hamasaki et al. 2015[a] [101]	2/3 (67%)	+	4
Education level	Chasens et al., 2012 [27]			1/1 (100%)	+	4
Health-related variables						
Health	Chasens et al., 2012 [27]			1/1 (100%)	+	4
BMI		Chasens et al., 2012 [27]		1/1 (100%)	−	4
Insomnia		Chasens et al., 2012 [27]		1/1 (100%)	−	4
Insulin sensitivity	Chasens et al., 2012 [27]			1/1 (100%)	+	4
Central adiposity		Chasens et al., 2012 [27]		1/1 (100%)	−	4
Body fat (in %)		Yates et al., 2008 [32]		1/1 (100%)	−	4
Waist circumference		Swindell et al., 2018 [31] Yates et al., 2008 [32]		2/2 (100%)	−	3
Systolic blood pressure			Swindell et al., 2018 [31]	0/1 (0%)	0	4
Diastolic blood pressure			Swindell et al., 2018 [31]	0/1 (0%)	0	4
Fasting insulin		Swindel et al., 2018 [31]		1/1 (100%)	−	4
Fasting glucose		Yates et al., 2008 [32]	Swindell et al., 2018 [31] Yates et al., 2013 [33]	1/3 (33%)	?	4
2-h plasma glucose		Swindell et al., 2018 [31] Yates et al., 2008 [32] Yates et al., 2013 [33]		3/3 (100%)	−	3
HbA1c			Swindell et al., 2018 [31] Yates et al., 2013 [33]	0/2 (0%)	0	3
HOMA-IR		Swindell et al., 2018 [31]		1/1 (100%)	−	4
Triglycerides		Swindell et al., 2018 [31] Yates et al., 2008 [32]		2/2 (100%)	−	3
Total cholesterol			Swindell et al., 2018 [31]	0/1 (0%)	0	4
HDL-cholesterol	Swindell et al., 2018 [31] Yates et al., 2008 [32]			2/2 (100%)	+	3
LDL-cholesterol			Swindell et al., 2018 [31]	0/1 (0%)	0	4
CRP		Swindell et al., 2018 [31]		1/1 (100%)	−	4
Obstructive sleep apnea severity			Mohklesi et al., 2021 [102]	0/1 (0%)	0	4
Pain/discomfort		Yates et al., 2008 [32]		1/1 (100%)	−	4
Behavioral variables						
Perceived competence			De Man et al., 2020 [100]	0/1 (0%)	0	4
Illness perceptions			Yates et al., 2008 [32]	0/1 (0%)	0	4
Mobility		Yates et al., 2008 [32]		1/1 (100%)	−	4
Self-care		Yates et al., 2008 [32]		1/1 (100%)	−	4
Interpersonal variables						
Perceived relatedness	De Man et al., 2020 [100]			1/1 (100%)	+	4
Environmental variables						
Physical environmental variables						
Not reported						
Perceived environmental variables						

Abbreviations: PA, physical activity; BMI, Body Mass Index; HbA1c, Hemoglobin A1c; HOMA-IR, Homeostatic Model Assessment of Insulin Resistance; HDL-cholesterol, high-density lipoprotein cholesterol; LDL-cholesterol, low-density lipoprotein cholesterol; CRP, c-reactive protein.

[a] Hamasaki H, Noda M, Moriyama S, Yoshikawa R, Katsuyama H, Sako A et al. Daily Physical Activity Assessed by a Triaxial Accelerometer Is Beneficially Associated with Waist Circumference, Serum Triglycerides, and Insulin Resistance in Japanese Patients with Prediabetes or Untreated Early Type 2 Diabetes. J Diabetes Res. 2015; 2015. Epub 20150510. https://doi.org/10.1155/2015/526201. PubMed PMID: 26064983; PubMed Central PMCID: PMC4331997.

[b] Summary code is an overall summary of the findings for each variable separately.

[c] n = Number of studies that report support for the direction of the association; N = number of studies that have investigated and reported on possible associations between the variable and total PA.

[d] Shows the direction of the individual/summary association.

[e] Based on the Evidence-Base Guideline Development method (Meeus et al. [33]).

(9.0%) of people with prediabetes [27–33], in 66 studies (84.6%) of people with T2D [34–99], and in five studies (6.4%) of both populations [100–104]. No study has investigated the explanatory variables of integrated 24-h movement behaviors. One study (1.3%) investigated the explanatory variables of all three behaviors in isolation [60], four studies (5.1%) investigated the explanatory variables of a combination of sleep and PA [34,79,87,102], and 13 studies (16.7%) investigated the explanatory variables of a combination of PA and SB [31,39,44,48,49,54,56,58,66,68,81,82,103]. Most studies have investigated the explanatory variables of a single movement behavior. In total, 40 studies (51.3%) investigated PA in isolation [27,28,32,33,37,38,40–43,45–47,50–52,57,59,63,64,67,72–78,83,85,86,89–91,93,95,99–101,105], six studies (7.7%) investigated SB in isolation [35,69–71,96,104] and 14 studies (17.9%) investigated sleep in isolation [29,36,53,55,61,62,65,80,84,88,92,94,98,106]. The majority (80%) of the included studies were cross-sectional of which 2% derived from randomized controlled trial baseline measurements. More information about the included study designs is provided in Supplementary file 4. Objective measurement devices differed across studies with accelerometry being the most commonly used device (58%) (Fig. 2). More details on the study characteristics can be found in Supplementary file 5.

3.2. Risk of bias and level of evidence

Sixty studies (76.9%) had a low risk of bias, 15 studies (19.2%) had a moderate risk of bias and three studies (3.8%) had a high risk of bias. Item 8 ("use of an appropriate statistical analysis") was most often scored with "yes", item 5 ("identification of confounding factors") and item 6 ("use of strategies to deal with confounding factors") were most often scored with "no". According to the level of evidence, most of the studies (83.3%) obtained level C, seven studies (9%) obtained level B and six studies (7.7%) obtained level A2. More information about the risk of bias and level of evidence can be found in Supplementary file 6.

3.3. Explanatory variables of 24-h movement behaviors

No study has investigated the explanatory variables of integrated 24-h movement behaviors in people with prediabetes or T2D. Therefore, the explanatory variables of each single movement behavior, investigated in a minimum of two independent studies, will be discussed separately for each population. Fig. 3 provides an overview of the explanatory variables of PA, SB and sleep in both populations classified according to the three domains of the SEM.

3.4. Explanatory variables of 24-h movement behaviors in people with prediabetes

No explanatory variables of sleep, SB, LPA or MVPA were investigated in a minimum of two studies. An overview of all the studied explanatory variables of total sleep duration, SB, LPA and MVPA in people with prediabetes are provided in Tables 1–4 respectively.

3.5. Explanatory variables of total physical activity

An overview of all the explanatory variables of total PA in people with prediabetes is provided in Table 5.

3.5.1. Intrapersonal level

One socio-demographic variable of total PA was investigated in a minimum of two studies. The results showed that being male was associated with more time spent in total PA (2/3, 67%, strength of conclusion level 4) [27,30,101].

Six health-related variables related to total PA were investigated in a minimum of two independent studies. A lower waist circumference and lower 2-h plasma glucose and triglyceride levels were associated with more time spent in total PA (2/2, 100%; 3/3, 100%, 2/2, 100%, respectively, strength of conclusion level 3) [31–33]. A positive association was found between total PA and HDL-cholesterol, with more time spent in total PA in people with higher levels of HDL-cholesterol (2/2, 100%, strength of conclusion level 3) [31,32]. No association was found between HbA1c and time spent in total PA and an indeterminate result was found for fasting glucose (0/2, 0%, strength of conclusion level 3; 1/3, 33%, strength of conclusion level 4, respectively) [31–33].

3.6. Explanatory variables of 24-h movement behaviors in people with T2D

3.6.1. Explanatory variables of sleep

An overview of all the explanatory variables of total sleep duration in people with T2D is provided in Table 6.

3.6.2. Intrapersonal level

Sex and age were the only socio-demographic variables investigated in two independent studies, showing an indeterminate association with sleep duration (1/2, 50%; 1/2, 50% respectively, strength of conclusion level 4) [55,87,98].

Three health-related variables of sleep duration were investigated in a minimum of two independent studies. A lower HbA1C level was associated with a longer sleep duration (2/3, 67%, strength of conclusion level 4) [80,87,88]. No association was found between sleep duration and obstructive sleep apnea or diabetic retinopathy (0/2, 0%; 0/2, 0%, respectively, strength of conclusion level 3) [53,65,80,84].

3.7. Explanatory variables of sedentary behavior

An overview of all the explanatory variables of SB in people with T2D is provided in Table 7.

3.7.1. Intrapersonal level

Two socio-demographic variables were investigated in a minimum of two independent studies. An older age was associated with more time spent sedentary (4/4, 100%, strength of conclusion level 3) [39,58,68,96]. No association was found between sex and SB (2/9, 22%, strength of conclusion level 4) [39,44,49,54,56,67,68,81].

The most frequently studied health-related variables were HbA1c, waist circumference and Body Mass Index (BMI). A higher HbA1c level, greater waist circumference and BMI were associated with more time spent sedentary (2/3, 66%, strength of conclusion level 4; 3/3, 100%, strength of conclusion level 2; 3/3, 100%, strength of conclusion level 3, respectively) [39,48,49,68,81,96]. A higher HDL-cholesterol level was associated with less time spent sedentary (2/2, 100%, strength of conclusion level 2) [48,49]. No association was found between SB and fatigue (0/2, 0%, strength of conclusion level 3) [35,76].

Time spent in MVPA was the only behavioral variable investigated in

Table 6
Explanatory variables of sleep duration in people with T2D and direction and strength of association.

	Related to sleep duration		Unrelated to sleep duration	Summary code[a]		Strength of conclusion[d]
	Positive association	Negative association		n/N for row (%)[b]	Association (+/−/0/?)[c]	
Intrapersonal variables						
Socio-demographic variables						
Age	Magri et al., 2023 [98]		Weatherall et al., 2018 [87]	1/2 (50%)	?	4
Education status			Weatherall et al., 2018 [87]	0/1 (0%)	0	4
Household income		Weatherall et al., 2018 [87]		1/1 (100%)	–	4
Sex (male)		Foster et al., 2009 [55]	Weatherall et al., 2018 [87]	1/2 (50%)	?	4
Race			Weatherall et al., 2018 [87]	0/1 (0%)	0	4
Marital status			Weatherall et al., 2018 [87]	0/1 (0%)	0	4
Health-related variables						
Diabetic retinopathy			Reutrakul et al., 2020 [80] Sirisreetreerux et al., 2021 [84]	0/2 (0%)	0	3
HbA1c		Reutrakul et al., 2020 [80] Whitaker et al., 2018 [88]	Weatherall et al., 2018 [87]	2/3 (67%)	–	4
Health-related quality of life (EQ-5D-5 L)			Johnson et al., 2017 [94]	0/1 (0%)	0	4
Health-related quality of life (SF-12 mental composite summary)		Johnson et al., 2017 [94]		1/1 (100%)	–	4
Health-related quality of life (SF-12 physical composite summary)			Johnson et al., 2017 [94]	0/1 (0%)	0	4
MT2 mutation			Imam et al., 2020 [61]	0/1 (0%)	0	4
Obstructive sleep apnea			Lam et al., 2010 [65] Ding et al., 2022 [53]	0/2 (0%)	0	3
Metformin therapy/intake	Kajbaf et al., 2014 [62]			1/1 (100%)	+	4
Insomnia			Alshehri et al., 2020 [36]	0/1 (0%)	0	4
Cardiovascular risk [e]		Hein et al., 2022 [92]		1/1 (100%)	–	4
Microalbuminuria		Magri et al., 2023 [98]		1/1 (100%)	–	4
LDL-cholesterol		Magri et al., 2023 [98]		1/1 (100%)	–	4
Time in range			Lee et al., 2023 [97]	0/1 (0%)	0	4
Time above range			Lee et al., 2023 [97]	0/1 (0%)	0	4
Time below range			Lee et al., 2023 [97]	0/1 (0%)	0	4
Standard deviation of glucose			Lee et al., 2023 [97]	0/1 (0%)	0	4
Coefficient of variation			Lee et al., 2023 [97]	0/1 (0%)	0	4
Behavioral variables						
Chronotype (Morning < evening/ Intermediate < evening)			Henson et al., 2020 [60]	0/1 (0%)	0	4
Interpersonal variables						
Ramadan		Alghamdi et al., 2020 [34]		1/1 (100%)	–	3
Environmental variables						
Physical environmental variables						
Hospitalization			Pupier et al., 2018 [79]	0/1 (0%)	0	4
Perceived environmental variables						
Not reported						

Abbreviations: T2D, type 2 diabetes; HbA1c, Hemoglobin A1c; SF, Short form; MT2 mutation, melatonin receptor 2 mutation.
[a] Summary code is an overall summary of the findings for each variable separately.
[b] n = Number of studies that report support for the direction of the association; N = number of studies that have investigated and reported on possible associations between the variable and sleep duration.
[c] Shows the direction of the individual/summary association.
[d] Based on the Evidence-Base Guideline Development method (Meeus et al. [33]).
[e] Based on the SCORE index calculated by five risk factors: age, sex, smoking status, systolic blood pressure and total cholesterol. The SCORE index estimates the risk of 10-year fatal cardiovascular event. A SCORE index <5% is considered to be a low risk of CVD and a SCORE index ≥5% was considered to be a high risk of CVD.

Table 7
Explanatory variables of SB in people withT2D and direction and strength of association.

	Related to SB		Unrelated to SB	Summary code[a]		Strength of conclusion[d]
	Positive association	Negative association		n/N for row (%)[b]	Association (+/−/0/?)[c]	
Intrapersonal variables						
Socio-demographic variables						
Sex (male)	Balducci et al., 2017 [39] Mathe et al., 2017 [68]	Rowlands et al., 2021 [81] Booth et al., 2022[e] [44]	Cooper et al., 2014 [49] Falconer et al., 2014 [54] Fritschi et al., 2016 [56] Manyara et al., 2021 [67] Booth et al., 2022[f] [44]	2/9 (22%)	0	4
Age	Balducci et al., 2017 [39] Mathe et al., 2017 [68] Guo et al., 2015 [58] Colomer et al., 2022 [96]			4/4 (100%)	+	3
Education		Mathe et al., 2017 [68]		1/1 (100%)	–	4
Employment		Mathe et al., 2017 [68]		1/1 (100%)	–	4
Ethnicity			Mathe et al., 2017 [68]	0/1 (0%)	0	4
Income			Mathe et al., 2017 [68]	0/1 (0%)	0	4
Smoking (smoker)		Mathe et al., 2017 [68]		1/1 (100%)	–	4
Health-related variables						
HbA1c	Balducci et al., 2017 [39] Rowlands et al., 2021 [81]		Cooper et al., 2014 [49]	2/3 (66%)	+	4
BMI	Mathe et al., 2017 [68] Rowlands et *al.* 2021 [81] Colomer et al., 2022 [96]			3/3 (100%)	+	3
Waist circumference	Balducci et al., 2017 [39] Cooper et al., 2014 [49] Cooper et al., 2012 [48]			3/3 (100%)	+	2
hs-CRP	Balducci et al., 2017 [39]			1/1 (100%)	+	4
Triacylglycerol	Cooper et al., 2014 [49]			1/1 (100%)	+	4
Metabolic risk[g]	Cooper et al., 2014 [49]			1/1 (100%)	+	4
HDL-cholesterol		Cooper et al., 2014 [49] Cooper et al., 2012 [48]		2/2 (100%)	–	2
Systolic blood pressure			Cooper et al., 2014 [49]	0/1 (0%)	0	4
Insulin	Cooper et al., 2012 [48]			1/1 (100%)	+	4
HOMA-IR	Cooper et al., 2012 [48]			1/1 (100%)	+	4
Physical activity energy expenditure			Lamb et al., 2016 [66]	0/1 (0%)	0	2
Wake time mean glucose			McMillan et al., 2020 [69]	0/1 (0%)	0	4
Glucose standard deviation			McMillan et al., 2020 [69]	0/1 (0%)	0	4
Glucose range			McMillan et al., 2020 [69]	0/1 (0%)	0	4
Glucose coefficient of variation			McMillan et al., 2020 [69]	0/1 (0%)	0	4

(*continued on next page*)

Table 7 (*continued*)

	Related to SB		Unrelated to SB	Summary code[a]		Strength of conclusion[d]
	Positive association	Negative association		n/N for row (%)[b]	Association (+/−/0/?)[c]	
Glucose CONGA			McMillan et al., 2020 [69]	0/1 (0%)	0	4
Average glucose blood level	Alothman et al., 2020 [35]			1/1 (100%)	+	4
Cardiorespiratory fitness		Cooper et al., 2014 [49]		1/1 (100%)	–	4
Diabetes duration			Mathe et al., 2017 [68]	0/1 (0%)	0	4
Nocturia	Morris et al., 2016 [70]			1/1 (100%)	+	4
Fatigue			Poppe et al., 2021 [76] Alothman et al., 2020 [35]	0/2 (0%)	0	3
Stress			Poppe et al., 2021 [76]	0/1 (0%)	0	4
Pain			Poppe et al., 2021 [76]	0/1 (0%)	0	4
Neck pain			Dzakpasu et al., 2023 [104]	0/1 (0%)	0	4
Shoulder pain			Dzakpasu et al., 2023 [104]	0/1 (0%)	0	4
Low back pain			Dzakpasu et al., 2023 [104]	0/1 (0%)	0	4
Knee pain	Dzakpasu et al., 2023 [104]			1/1 (100%)	+	4
Nausea/dizziness			Poppe et al., 2021 [76]	0/1 (0%)	0	4
Numbness/tingling			Poppe et al., 2021 [76]	0/1 (0%)	0	4
Sadness			Poppe et al., 2021 [76]	0/1 (0%)	0	4
Well-being			Alothman et al., 2020 [35]	0/1 (0%)	0	4
Physical function			Alothman et al., 2020 [35]	0/1 (0%)	0	4
Behavioral variables						
Chronotype (Morning < evening/ Intermediate < evening)	Henson et al., 2020 [60]			1/1 (100%)	+	4
MVPA		Cooper et al., 2014 [49]	Lamb et al., 2016 [66]	1/2 (50%)	?	4
Interpersonal variables						
Not reported						
Environmental variables						
Physical environmental variables						
Time of day (morning)	Paing et al., 2020 [71]			1/1 (100%)	+	4
Hospitalized			Pupier et al., 2018 [79]	0/1 (0%)	0	4
Perceived environmental variables						
Not reported						

Abbreviations: SB, sedentary behavior; T2D, type 2 diabetes; HbA1c; Hemoglobin A1c; BMI, Body Mass Index; Hs-CRP, high-sensitivity C-reactive protein; HDL-cholesterol, High-density lipoprotein cholesterol; HOMA-IR, homeostatic model assessment for insulin resistance; glucose CONGA, continuous overall net glycemic action; MVPA, moderate to vigorous physical activity.

[a] Summary code is an overall summary of the findings for each variable separately.

[b] n = Number of studies that report support for the direction of the association; N = number of studies that have investigated and reported on possible associations between the variable and sedentary behavior.

[c] Shows the direction of the individual/summary association.

[d] Based on the Evidence-Base Guideline Development method (Meeus et al. [33]).

[e] Proportion of time spent sedentary per day.

[f] Sedentary time (h/day).

[g] Metabolic risk is calculated by summing standardized values for waist circumference, fasting triaglycerol, HbA1c and systolic blood pressure and the inverse of HDL-cholesterol.

two independent studies, showing an indeterminate association with time spent sedentary (1/2, 50%, strength of conclusion level 4) [49,66].

3.8. Explanatory variables of light physical activity

An overview of all the explanatory variables of LPA in people with T2D is provided in Table 8.

3.8.1. Intrapersonal level

Two socio-demographic variables were explored in a minimum of two independent studies. The results indicated that men spent less time in LPA than women did (3/5, 60%, strength of conclusion level 4) [39,44,56,68,82]. An indeterminate association was found between age and LPA (1/2, 50%, strength of conclusion level 4) [39,68].

BMI was the only health-related variable investigated in two

Table 8
Explanatory variables of LPA in people withT2D and direction and strength of association.

	Related to LPA		Unrelated to LPA	Summary code[a]		Strength of conclusion[d]
	Positive association	Negative association		n/N for row (%)[b]	Association (+/−/0/?)[c]	
Intrapersonal variables						
Socio-demographic variables						
Age		Balducci et al., 2017 [39]	Mathe et al., 2017 [68]	1/2 (50%)	−	4
Sex (male)	Booth et al., 2022 [44]	Sardinha et al., 2017 [82] Balducci et al., 2017 [39] Mathe et al., 2017 [68]	Fritschi et *al.* 2016 [56]	3/5 (60%)	−	4
Education			Mathe et al., 2017 [68]	1/1 (100%)	0	4
Employment			Mathe et al., 2017 [68]	1/1 (100%)	0	4
Retired			Mathe et al., 2017 [68]	1/1 (100%)	0	4
Ethnicity (non-Caucasian)			Mathe et al., 2017 [68]	1/1 (100%)	0	4
Income			Mathe et al., 2017 [68]	1/1 (100%)	0	4
Smoking status			Mathe et al., 2017 [68]	1/1 (100%)	0	4
Marital status			Mathe et al., 2017 [68]	1/1 (100%)	0	4
Health-related variables						
HbA1c		Balducci et al., 2017 [39]		1/1 (100%)	−	4
BMI		Balducci et al., 2017 [39] Mathe et al., 2017 [68]		2/2 (100%)	−	3
High sensitivity-C-reactive protein		Balducci et al., 2017 [39]		1/1 (100%)		4
Chronotype preference[e]		Henson et al., 2020 [60]		1/1 (100%)	−	4
Stress			Poppe et al., 2021 [76]	1/1 (100%)	0	4
Diabetes duration			Mathe et al., 2017 [68]	1/1 (100%)	0	4
Fatigue			Poppe et al., 2021 [76]	1/1 (100%)	0	4
Pain			Poppe et al., 2021 [76]	1/1 (100%)	0	4
Nausea/dizziness			Poppe et al., 2021 [76]	1/1 (100%)	0	4
Numbness/tingling			Poppe et al., 2021 [76]	1/1 (100%)	0	4
Sadness			Poppe et al., 2021 [76]	1/1 (100%)	0	4
Behavioral variables						
Exercise[f]			An et al., 2020 [37]	0/1 (0%)	0	4
Interpersonal variables						
Ramadan			Alghamdi et al., 2020 [34]	1/1 (100%)	0	3
Environmental variables						
Physical environmental variables						
Amount of PA equipment in the home	De Greef et al., 2011 [52]			1/1 (100%)	+	4
Perceived environmental variables						
Walking infrastructure[g]		De Greef et al., 2011 [52]		1/1 (100%)	−	4

Abbreviations: LPA, light physical activity; T2D, type 2 diabetes; HbA1c, Hemoglobin A1c; BMI, Body Mass Index; PA, physical activity.
[a] Summary code is an overall summary of the findings for each variable separately.
[b] n = Number of studies that report support for the direction of the association; N = number of studies that have investigated and reported on possible associations between the variable and LPA.
[c] Shows the direction of the individual/summary association.
[d] Based on the Evidence-Base Guideline Development method (Meeus et al. [33]).
[e] "a diurnal characteristic, identifies individuals as having a preference for morning (i.e., go to bed early and get up early), evening (ie, go to bed late and get up late) or neither (intermediate)".
[f] Self-reported for at least 30 min per day for 3 days per week for the past 3 months or longer.
[g] Perceiving lower availability and quality of walking infrastructure.

independent studies and was negatively associated with time spent in LPA (2/2, 100%, strength of conclusion level 3) [39,68].

3.9. Explanatory variables of moderate to vigorous physical activity

An overview of all the explanatory variables of MVPA in people with T2D is provided in Table 9.

3.9.1. Intrapersonal level

Five socio-demographic variables were explored in a minimum of two independent studies. Sex was studied in 15 studies with 11 studies indicating that men performed more time in MVPA than women did (11/15, 73%, strength of conclusion level 4) [39,40,44,46,49,54,56,59,66–68,74,81,90,93]. Age was negatively associated with MVPA, less time was spent in MVPA with increasing age (7/10, 70%, strength of conclusion level 4) [39,40,46,47,58,68,74,81,90,93]. People with a higher income or a higher education level spent time more time in MVPA (2/2, 100%, strength of conclusion level 3; 2/3, 67%, strength of conclusion level 4, respectively) [40,47,68]. Additionally, no association was found between MVPA and ethnicity (2/5, 40%, strength of conclusion level 4) [40,59,68,93].

Nine health-related variables were explored in a minimum of two

Table 9
Explanatory variables of MVPA in people withT2D and direction and strength of association.

	Related to MVPA		Unrelated to MVPA	Summary code[a]		Strength of conclusion[d]
	Positive association	Negative association		n/N for row (%)[b]	Association (+/−/0/?)[c]	
Interpersonal variables						
Socio-demographic variables						
Age		Balducci et al., 2017 [39] Bazargan-Hejazi et al., 2017 [40] Jakicic et al., 2010[e] [93] Rowlands et al., 2021 [81] Chlebowy et al., 2016 [47] Pizzol et al., 2019 [74] Mathe et al., 2017 [68] Guo et al., 2015[f] [58]	Castonguay & Miquelon 2018 [46] Zhu et al., 2021 [90] Guo et al., 2015[g] [58] Jakicic et al., 2010[h] [93]	8/12 (67%)	−	4
Sex (being male)	Bazargan-Hejazi et al., 2017 [40] Cooper et al., 2014 [49] Falconer et al., 2014 [54] Lamb et al., 2016 [66] Manyara et al., 2021 [67] Rowlands et al., 2021 [81] Balducci et al., 2017 [39] Jakicic et al., 2010[h] [93] Pizzol et al., 2019 [74] Mathe et al., 2017 [68] Booth et al., 2022 [44]	Castonguay & Miquelon 2018 [46]	Fritschi et al., 2016 [56] Jakicic et al., 2010[e] [93] Helgeson et al., 2021 [59] Zhu et al., 2021 [90]	11/15 (73%)	+	4
Race/Ethnicity	Bazargan-Hejazi et al.,2017[g,i] [40] Jakicic et al., 2010[j,k] [93]		Jakicic et al., 2010[l] [93] Mathe et al., 2017 [68] Helgeson et al., 2021 [59]	2/5 (40%)	0	4
Employed	Mathe et al., 2017 [68]			1/1 (100%)	+	4
Smoking status			Mathe et al., 2017 [68]	0/1 (0%)	0	4
Income	Bazargan-Hejazi et al., 2017 [40] Mathe et al., 2017 [68]			2/2 (100%)	+	3
Education	Bazargan-Hejazi et al., 2017 [40] Chlebowy et al., 2016 [47]		Mathe et al., 2017 [68]	2/3 (67%)	+	4
Marital status		Mathe et al., 2017 [68]		1/1 (100%)	−	4
Health-related variables						
HbA1c		Balducci et al., 2017 [39]	Cooper et al., 2014 [49] Dauriz et al., 2018 [51]	1/3 (33%)	0	4
HDL-cholesterol	Dauriz et al., 2018 [51]		Cooper et al., 2014 [49] Cooper et al., 2012 [48]	1/3 (33%)	0	4
Triacylglycerol			Cooper et al., 2014 [49]	0/1 (0%)	0	4
Insulin		Cooper et al., 2012 [48]		1/1 (100%)	−	3
HOMA-IR		Cooper et al., 2012 [48]		1/1 (100%)	−	3
Fasting plasma glucose			Dauriz et al., 2018 [51]	0/1 (0%)	0	4
2-h plasma glucose			Dauriz et al., 2018 [51]	0/1 (0%)	0	4
Triglycerides		Dauriz et al., 2018[m] [51]	Dauriz et al., 2018[n] [51]	1/2 (50%)	?	4
Insulin sensitivity	Dauriz et al., 2018 [51]			1/1 (100%)	+	4
Waist circumference		Balducci et al., 2017 [39] Cooper et al., 2012 [48] Dauriz et al., 2018[m] [51]	Cooper et al., 2014 [49] Dauriz et al., 2018[n] [51]	3/5 (60%)	−	4
BMI		Bazargan-Hejazi *et al.*2017[o] [40] Castonguay & Miquelon 2018 [46] Dauriz et al., 2018[m] [51] Jakicic et al., 2010 [93] Rowlands et al., 2021 [81] Mathe et al., 2017 [68]	Dauriz et al., 2018[n] [51] Zhu et al., 2021 [90]	6/8 (75%)	−	4
Fat mass (%)		Dauriz et al., 2018[m] [51]	Dauriz et al., 2018[n] [51]	1/2 (50%)	?	4
Disposition index[p]			Dauriz et al., 2018 [51]	0/1 (0%)	0	4
Systolic blood pressure		Cooper et al., 2014 [49]		1/1 (100%)	−	4
Cardiovascular disease history	Jakicic et al., 2010[e] [93]		Jakicic et al., 2010[h] [93]	1/2 (50%)	?	4
Comorbidities		Bazargan-Hejazi et al., 2017 [40]		1/1 (100%)	−	4
Metabolic risk[q]			Cooper et al., 2014 [49]	0/1 (0%)	0	3
Glucose AUC			Dauriz et al., 2018 [51]	0/1 (0%)	0	4

(*continued on next page*)

Table 9 (*continued*)

	Related to MVPA		Unrelated to MVPA	Summary code[a]		Strength of conclusion[d]
	Positive association	Negative association		n/N for row (%)[b]	Association (+/−/0/?)[c]	
Diabetes medication			Bazargan-Hejazi et al.,2017 [40] Jakicic et al., 2010 [93]	0/2 (0%)	0	3
Hyperglycemia symptoms		Castonguay & Miquelon 2018 [46]		1/1 (100%)	–	3
Diabetes duration		Zhu et al., 2021 [90]	Mathe et al., 2017 [68]	1/2 (50%)	?	4
Physical function	Rowlands et al., 2021 [81]			1/1 (100%)	+	4
Cardiorespiratory fitness	Cooper et al., 2014 [49] Jakicic et al., 2010 [93]			2/2 (100%)	+	4
Fatigue		Castonguay & Miquelon 2018 [46] Zhu et al., 2021 [90]	Poppe et al., 2021 [76]	2/3 (67%)	–	4
Cognitive distress		Castonguay & Miquelon 2018 [46]		1/1 (100%)	–	3
Stress			Poppe et al., 2021 [76]	0/1 (0%)	0	4
Depressive symptoms		Rowlands et al., 2021 [81] Pizzol et al., 2019 [74]		2/2 (100%)	–	3
Pain			Poppe et al., 2021 [76]	0/1 (0%)	0	4
Nausea/dizziness			Poppe et al., 2021 [76]	0/1 (0%)	0	4
Numbness/tingling			Poppe et al., 2021 [76]	0/1 (0%)	0	4
Sadness			Poppe et al., 2021 [76]	0/1 (0%)	0	4
Behavioral variables						
Exercise	An et al., 2020 [37]			1/1 (100%)	+	4
Physical activity energy expenditure	Cooper et al., 2014 [49] Lamb et al., 2016 [66]			2/2 (100%)	+	2
Vegetarian diet			Bazargan-Hejazi et al., 2017 [40]	0/1 (0%)	0	4
Intrinsic regulations[r]	Castonguay & Miquelon 2018 [46]			1/1 (100%)	+	3
Introject regulations[s]			Castonguay & Miquelon 2018 [46]	0/1 (0%)	0	3
Amotivation regulations			Castonguay & Miquelon 2018 [46]	0/1 (0%)	0	3
Identified regulations[t]			Castonguay & Miquelon 2018 [46]	0/1 (0%)	0	3
Sedentary time		Cooper et al., 2014 [49]		1/1 (100%)	–	4
Chronotype		Henson et al., 2020[u] [60]		1/1 (100%)	–	4
Restorative sleep	Zhu et al., 2021 [90]			1/1 (100%)	+	4
Extrinsic regulations[v]		Castonguay & Miquelon 2018 [46]		1/1 (100%)	–	3
Interpersonal variables						
Ramadam			Alghamdi et al., 2020 [34]	0/1 (0%)	0	3
Environmental variables						
Physical environmental variables						
Walkability	De Greef et al., 2011 [52]			1/1 (100%)	+	4
Perceived environmental variables						
Aesthetics of physical environment	De Greef et al., 2011 [52]			1/1 (100%)	+	4

Abbreviations: MVPA, moderate to vigorous physical activity; T2D, type 2 diabetes; HbA1c, Hemoglobin A1c; HDL-cholesterol, High density lipoprotein cholesterol; HOMA-IR, homeostasis model assessment for insulin resistance; BMI, Body Mass Index; glucose AUC, glucose area under the curve; MET, metabolic equivalent of task;

[a] Summary code is an overall summary of the findings for each variable separately.
[b] n = Number of studies that report support for the direction of the association; N = number of studies that have investigated and reported on possible associations between the variable and MVPA.
[c] Shows the direction of the individual/summary association.
[d] Based on the Evidence-Base Guideline Development method (Meeus et al. [33]).
[e] METs per minute.
[f] Only in men.
[g] Only in women.
[h] Bouts per day, minutes per bout and total MET-minutes.
[i] Hispanic > Whites and African Americans.
[j] White & Hispanic > African American/other.
[k] Bouts per minute and minutes per bout.
[l] METs per minute and total MET-minutes.
[m] Daily physical activity ≥3 MET
[n] Energy Expenditure≥ 3 MET
[o] Trend towards significance (p = 0.0771).
[p] A measure of insulin secretory compensation accounting for changing in insulin sensitivity.
[q] Metabolic risk is calculated by summing standardized values for waist circumference, fasting triaglycerol, HbA1c and systolic blood pressure and the inverse of HDL-cholesterol.

[r] Achieving an outcome because you are self-motivated and self-determined.
[s] A regulation which you partially internalize but not accept as one's own such as acting to avoid guild or enhance the ego.
[t] Achieving an outcome because it is considered as personally valuable and important to obtain.
[u] Morning > evening/Intermediate > evening.
[v] Acting to satisfy an eternal demand or receive a demand.

independent studies. A higher BMI and waist circumference were associated with less time spent in MVPA (6/7, 86%; 3/5, 60% respectively, strength of conclusion level 4) [39,40,46,48,49,51,68,81,90,93]. A higher cardiorespiratory fitness was associated with more time spent in MVPA (2/2, 100%, strength of conclusion level 4) [49,93]. Time spent in MVPA was negatively associated with depressive symptoms and fatigue (2/2, 100%, strength of conclusion level 3; 2/3, 67%, strength of conclusion level 4, respectively) [46,74,76,81,90]. An indeterminate association was found for diabetes duration (1/2, 50%, strength of conclusion level 4) [68,90]. Additionally, no associations were found between time spent in MVPA and HDL-cholesterol, HbA1c or diabetes medication (1/3, 33%, strength of conclusion level 4; 1/3, 33%, strength of conclusion level 4; 0/2, 0%, strength of conclusion level 3, respectively) [39,40,48,49,51,93].

One behavioral variable, i.e. physical activity energy expenditure, was investigated in a minimum of two studies showing a higher physical activity energy expenditure in people who spent more time in MVPA (2/2, 100%, strength of conclusion level 2) [49,66].

3.10. Explanatory variables of total physical activity

An overview of all the explanatory variables of total PA in people with T2D is provided in Table 10.

3.10.1. Intrapersonal level

Four socio-demographic variables were investigated in a minimum of two independent studies. Sex was the most frequently studied variable and showed an indeterminate association with time spent in total PA (5/11, 45%, strength of conclusion level 4) [44,63,64,66–68,73,75,81,87,95]. Age was negatively associated with total PA (3/4, 75%, strength of conclusion level 4) [57,64,85,87]. Educational level was not associated with time spent in total PA and an indeterminate result was found for ethnicity (1/3, 33%; 1/2, 50%, respectively, strength of conclusion level 4) [57,73,81,87].

Six health-related variables were investigated in a minimum of two independent studies. A higher BMI was associated with less time spent in total PA (5/8, 63%, strength of conclusion level 4) [51,57,81,83,85–87]. A negative association was found between waist circumference and time spent in total PA (3/4, 75%, strength of conclusion level 4) [49,51,99]. Moreover, neither HbA1c nor HDL cholesterol was associated with time spent in total PA (0/5, 0%, strength of conclusion level 3; 1/3, 33%, strength of conclusion level 4, respectively) [49–51,83,87]. An indeterminate association was found for systolic blood pressure and fat mass (2/4, 50, 1/2, 50%, respectively) [49–51,57,83,91,107].

3.11. Environmental level

One physical environmental variable, i.e. being hospitalized, and one perceived environmental variable, i.e. subjective walkability, were indeterminately associated with time spent in total PA (2/5, 40%, 1/2, 50% respectively, strength of conclusion level 4) [45,72,77,79].

4. Discussion

This systematic review aimed to summarize the explanatory variables of PA, SB and sleep in people with prediabetes or T2D. Based on this review, four gaps in the current evidence were identified. First, almost no explanatory variables of movement behaviors were investigated at the interpersonal or environmental levels. Second, in people with prediabetes, little is known about the explanatory variables of single movement behaviors. Third, information about the explanatory variables of objectively measured sleep and LPA in people with prediabetes or T2D is scarce. Last, until now there has been no focus on the explanatory variables of the 24-h movement behavior composition in both populations.

First, the finding that the majority of the examined factors pertained to the intrapersonal level, with minimal exploration at the interpersonal and environmental levels, suggests a deficiency in adopting a socio-ecological approach. This observation is noteworthy given the recommendation of this multilevel approach by the Ottawa Charter for Health Promotion [108]. Most behavior change models focus only on the intrapersonal level, however, the SEM broadens this focus to the interrelations of intrapersonal factors with sociocultural and physical surroundings [16]. The beneficial effects of behavioral change interventions (i.e. promoting PA, limiting SB and optimizing sleep) by focusing on the interrelation of the socio-ecological levels have already been demonstrated in healthy individuals [109–113] and people with T2D [114] but are unexplored in people with prediabetes. In future research, it is recommended to apply the SEM methodology to explore the factors influencing 24-h movement behaviors of people with prediabetes or T2D to formulate recommendations for future intervention studies.

The most investigated intrapersonal factors were socio-demographic and health-related variables. For example, age and sex were consistently investigated in at least one study across all behaviors except for sleep in people with prediabetes. Increasing age was consistently associated with lower LPA, MVPA and total PA levels and higher SB levels in both populations but additional research is needed in people with prediabetes to determine these associations. Similar trends are identified in healthy populations which can be explained by a decline in functional capacity and comorbidities with advancing age [115–120]. This finding suggested that 24-h movement behavior compositions might become less optimal with increasing age in people with prediabetes or T2D. This highlights the potential need for the development of interventions stratified by different age groups. Regarding sex, differences in sleep and PA between men and women with T2D were found. Men with T2D tend to sleep less, perform less LPA but more MVPA compared to women with T2D who have lower levels of MVPA and total PA but higher levels of LPA. Studies in healthy individuals also support this sexual dimorphism in movement behaviors [121]. Although additional research is needed to confirm this phenomenon in people with prediabetes, our results suggest that it is important to differentiate between men and women in future interventions aiming to optimize 24-h movement behaviors.

Among the health-related variables, HbA1c was consistently investigated across all movement behaviors except for LPA in people with prediabetes. However, comparison with the findings of other studies is difficult since associations between movement behaviors and health outcomes can be investigated in two directions, and most studies have examined the influence of a movement behavior (e.g. PA) on a health outcome (e.g. HbA1c) while this review investigated the inverse association. In people with T2D, BMI was investigated across all behaviors except sleep. A lower BMI was consistently associated with more time spent in total PA, MVPA and LPA, while a higher BMI was associated with more time spent sedentary. Recent research has also shown that the time spent on 24-h movement behaviors in adults with T2D differs according to weight status with adults being obese spending less time in LPA, MVPA and sleep than adults being normal weight or overweight [13].

Almost no behavioral variables were investigated in both populations. Since interventions targeting behavioral change often rely on causal determinants to effectively change behavior, more additional research on the behavioral explanatory variables of 24-h movement

Table 10
Explanatory variables of total PA in people with T2D and direction and strength of association.

	Related to total PA		Unrelated to total PA	Summary code[b]		Level of evidence[e]
	Positive association	Negative association		n/N for row (%)[c]	Association (+/−/0/?)[d]	
Intrapersonal variables						
Socio-demographic variables						
Sex (male)	Mathe et al., 2017 [68] Manyara et al., 2021 [67] Kaur & Sandhu 2015 [63] Lamb et al., 2016 [66] Booth et al., 2022 [44]	Rowlands et al., 2021 [81] Weatherall et al., 2018 [87] Kelly et al., 2015 [64]	Phillips et al., 2016 [73] Plotnikoff et al., 2013 [75] Hamasaki et al. 2015[a] [95]	5/11 (45%)	?	4
Age		Kelly et al., 2015 [64] Strycker et al., 2007[f] [85] Fritschi et al., 2017 [57]	Weatherall et al., 2018 [87]	3/4 (75%)	–	4
Marital status			Weatherall et al., 2018 [87]	0/1 (0%)	0	4
Ethnicity (black/minority)		Rowlands et al., 2021 [81]	Weatherall et al., 2018 [87]	1/2 (50%)	?	4
Income	Bermudez-Milan et al., 2016 [41]			1/1 (100%)	+	4
Education level	Phillips et al., 2016 [73]		Weatherall et al., 2018 [87] Fritschi et al., 2017 [57]	1/3 (33%)	0	4
Employment	Weatherall et al., 2018 [87]			1/1 (100%)	+	4
Health-related variables						
BMI		Rowlands et al., 2021 [81] Dauriz et al., 2018 [51] Strycker et al., 2007[f] [85] Tudor-Locke et al., 2002[g] [86] Weatherall et al., 2018 [87]	Siddiqui et al., 2018 [83] Dauriz et al., 2018[h] [51] Fritschi et al., 2017 [57]	5/8 (63%)	–	4
Waist circumference		Dauriz et al., 2018 [51] Cooper et al., 2014 [49] Rowlands et al., 2023 [99]	Dauriz et al., 2018[h] [51]	3/4 (75%)	–	4
Fat mass (%)		Rowlands et al., 2023 [99]	Dauriz et al., 2018 [51]	1/2 (50%)	?	4
VO_2max	Bjørgaas et al., 2005 [43]			1/1 (100%)	+	4
Cardiorespiratory fitness	Cooper et al., 2014 [49]			1/1 (100%)	+	4
Perceived physical fitness	Bjørgaas et al., 2005 [43]			1/1 (0%)	+	4
Short physical performance battery score	Rowlands et al., 2023 [99]			1/1 (100%)	+	4
Sit-to-stand score	Rowlands et al., 2023 [99]			1/1 (100%)	+	4
Resting heart rate		Rowlands et al., 2023 [99]		1/1 (100%)	–	4
Systolic blood pressure		Dasgupta et al., 2017 [50] Zucatti et al., 2017[i] [91]	Siddiqui et al., 2018 [83] Cooper et al., 2014 [49]	2/4 (50%)	?	4
Diastolic blood pressure			Siddiqui et al., 2018 [83]	0/1 (0%)	0	3
HbA1c			Dasgupta et al., 2017 [50] Weatherall et al., 2018 [87] Siddiqui et al., 2018 [83] Cooper et al., 2014 [49] Dauriz et al., 2018[h] [51]	0/5 (0%)	0	3
HOMA-IR		Dasgupta et al., 2017 [50]		1/1 (100%)	–	4
LDL-cholesterol			Dasgupta et al., 2017 [50]	0/1 (0%)	0	4
HDL-cholesterol	Dauriz et al., 2018 [51]		Cooper et al., 2014 [49] Dauriz et al., 2018[h] [51]	1/3 (33%)	0	4
Triacylglycerol			Cooper et al., 2014 [49]	0/1 (0%)	0	4
Triglycerides		Dauriz et al., 2018 [51]	Dauriz et al., 2018[h] [51]	1/2 (50%)	?	4
Fasting plasma glucose			Dauriz et al., 2018 [51]	0/1 (0%)	0	4
2-h plasma glucose			Dauriz et al., 2018 [51]	0/1 (0%)	0	4
Glucose AUC			Dauriz et al., 2018 [51]	0/1 (0%)	0	4
Time in range			Lee et al., 2023 [97]	0/1 (0%)	0	4
Time above range			Lee et al., 2023 [97]	0/1 (0%)	0	4
Time below range			Lee et al., 2023 [97]	0/1 (0%)	0	4

(*continued on next page*)

Table 10 (*continued*)

	Related to total PA		Unrelated to total PA	Summary code[b]		Level of evidence[e]
	Positive association	Negative association		n/N for row (%)[c]	Association (+/−/0/?)[d]	
Standard deviation			Lee et al., 2023 [97]	0/1 (0%)	0	4
Coefficient of variation			Lee et al., 2023 [97]	0/1 (0%)	0	4
Disposition index[j]			Dauriz et al., 2018 [51]	0/1 (0%)	0	4
Insulin sensitivity	Dauriz et al., 2018 [51]			1/1 (100%)	+	4
Metabolic risk		Cooper et al., 2014 [49]		1/1 (100%)	−	4
T2D diagnosis		Preiss et al., 2014 [77]	Fritschi et al., 2017 [57]	1/2 (50%)	?	4
Medication	Weatherall et al., 2018 [87]			1/1 (100%)	+	4
Fatigue		Fritschi et al., 2017[k] [57]	Fritschi et al., 2017[l] [57]	1/2 (50%)	?	4
Executive function			Zabetian-Targhi et al., 2021 [89]	0/1 (0%)	0	4
Attention-processing speed			Zabetian-Targhi et al., 2021 [89]	0/1 (0%)	0	4
Verbal fluency			Zabetian-Targhi et al., 2021 [89]	0/1 (0%)	0	4
Verbal memory			Zabetian-Targhi et al., 2021 [89]	0/1 (0%)	0	4
Visual memory			Zabetian-Targhi et al., 2021 [89]	0/1 (0%)	0	4
Visuospatial function			Zabetian-Targhi et al., 2021 [89]	0/1 (0%)	0	4
Global cognition			Zabetian-Targhi et al., 2021 [89]	0/1 (0%)	0	4
Reactive hyperemia index	Baier et al., 2021 [38]			1/1 (100%)	+	3
Behavioral variables						
Perceived everyday activity			Bjørgaas et al., 2005 [43]	0/1 (0%)	0	4
Health beliefs	Phillips et al., 2016 [m] [73]		Phillips et al. 2016[n] [73]	1/2 (50%)	?	4
PA related concerns		Phillips et al., 2016 [73]		1/1 (100%)	−	4
Barriers for PA	Phillips et al., 2016 [73]			1/1 (100%)	+	4
Sedentary time		Cooper et al., 2014 [49]		1/1 (100%)	−	4
Wake after sleep onset			Fritschi et al., 2017 [57]	0/1 (0%)	0	4
Sleep efficiency			Fritschi et al., 2017 [57]	0/1 (0%)	0	4
Chronotype		Henson et al., 2020 [60]		1/1 (100%)	−	4
Interpersonal variables						
Racial discrimination			Bermudez-Milan et al., 2016 [41]	0/1 (0%)	0	4
Environmental variables						
Physical environmental variables						
Hospitalized		Pezzino et al. 2010[o] [72] Pupier et al. 2018[h] [79]	Preiss et al., 2014 [77] Pezzino et al., 2010 [72] Pupier et al. 2018[o] [79]	2/5 (40%)	?	4
Day of the week (weekday)		Bevier et al., 2020 [42]		1/1 (100%)	−	4
Home equipment	De Greef et al., 2011 [52]			1/1 (100%)	+	4
Objective walkability		Braver et al., 2021 [45]		1/1 (100%)	−	4
Perceived environmental variables						
Subjective walkability	Braver et al. 2021[p] [45]		Braver et al. 2021[q] [45]	1/2 (50%)	?	4

Abbreviations: PA, physical activity; T2D, type 2 diabetes; BMI, Body Mass Index; HbA1c, Hemoglobin A1c; HOMA-IR, homeostatic model assessment of insulin resistance; LDL-cholesterol, low-density lipoprotein cholesterol; HDL-cholesterol, high-density lipoprotein cholesterol; glucose AUC, glucose area under the curve;

[a] Hamasaki H, Kawashima Y, Adachi H, Moriyama S, Katsuyama H, Sako A et al. Associations between lower extremity muscle mass and metabolic parameters related to obesity in Japanese obese patients with type 2 diabetes. PeerJ. 2015; 3:942. Epub 20150505. https://doi.org/10.7717/peerj.942. PubMed PMID: 26175963; PubMed Central PMCID: PMC4499465.

[b] Summary code is an overall summary of the findings for each variable separately.

[c] n = Number of studies that report support for the direction of the association; N = number of studies that have investigated and reported on possible associations between the variable and total PA.

[d] Shows the direction of the individual/summary association.

[e] Based on the Evidence-Base Guideline Development method (Meeus et al. [33]).

[f] Postmenopausal women with T2D.

[g] 40–60 year old.

[h] Total energy expenditure.

[i] Less than 4873 steps/day.

[j] Metabolic risk is calculated by summing standardized values for waist circumference, fasting triaglycerol, HbA1c and systolic blood pressure and the inverse of HDL-cholesterol.

[k] Older group ($\geq$59 years).

[l] Younger group ($\leq$58 years).

[m] Habits.

[n] Necessity beliefs.

[o] Physical activity energy expenditure.

[p] Only in women.
[q] Only in men.

behaviors in people with prediabetes and people with T2D is necessary [122].

Next, no explanatory variables of 24-h movement behaviors at the interpersonal level in both populations and only one variable at the environmental level in people with T2D were investigated in two or more independent studies. Nevertheless, research in healthy individuals has shown a significant association between interpersonal variables, such as social support and modeling, and PA [123]. Furthermore, research in healthy individuals has shown that environmental variables (e.g. accessibility of facilities, aesthetics and opportunities for activity) have a significant impact on PA levels [124,125]. Further research targeting explanatory variables at the interpersonal and environmental levels is needed to provide recommendations for the development of 24-h movement behavior interventions incorporating multiple levels of the SEM in people with prediabetes and people with T2D [16].

Second, research on the explanatory variables of objectively measured PA, SB or sleep among people with prediabetes is scarce. This can be explained by the fact that prediabetes occurs mostly asymptomatically, making it difficult to target this population for research [126].

Third, it is remarkable that information on the explanatory variables of objectively measured LPA and sleep duration in people with prediabetes and people with T2D is scarce, especially since an increase in LPA can have an impact on health outcomes in both populations [12,127]. Reallocating time from SB to LPA is known to positively influence anthropometric (e.g. BMI, fat mass) and diabetes-specific (e.g. insulin levels) measures [11,12]. Furthermore, a systematic review summarizing the evidence of LPA on cardiometabolic health in adults with obesity and/or T2D showed that short bouts (2 min) of LPA and interruption of SB at least every 20 min significantly reduced (17.48%) postprandial glycemic control compared to a whole day of sitting without interruptions [128]. Additionally, reallocating time form SB to LPA is perceived to be more feasible among people with less functional capacity [128–130]. Regarding sleep, adults with T2D with a long sleep duration (≥9 h) tend to benefit regarding adiposity by taking time out of sleep and replacing it with more PA, whereas these benefits are not found for adults with a short-to-average sleep duration (≤7.5 h). Therefore, additional research is needed on the explanatory variables of sleep incorporating the importance of this U-shaped association [13].

Last, the results of this review underscore the lack of focus on 24-h movement behavior compositions in people with prediabetes and people with T2D. This is a large shortcoming since the shift in research from an isolated approach toward an integrated approach is already present and rapidly emerging in healthy and clinical populations [11,31,131].

4.1. Clinical relevance

An important step in the development of behavior change interventions is the identification of variables that determine the behavior of interest. This systematic review provides recommendations to guide the development of 24-h movement behavior interventions in people with prediabetes or T2D by summarizing the explanatory variables of these behaviors. The explanatory variables of the three movement behaviors were examined in parallel making it possible to identify similarities and differences in explanatory variables between the behaviors, which informs future 24-h movement behavior interventions. For example, this systematic review showed that future 24-h movement behavior interventions may differ according to sex and age. Therefore, based on available evidence, interventions for women with T2D should focus on encouraging participation in moderate to vigorous physical activities, while for men the focus should be on maintaining their physical activities with attention given to sufficient and qualitative sleep. With increasing age, interventions should primarily focus on interrupting SB and increasing LPA with continued attention given to increasing moderate to intense physical activity when possible. As sex and age are unmodifiable factors, future interventions should be stratified by these variables. However, additional insight into behavioral variables is essential as interventions can be developed to target these adaptable variables.

4.2. Strengths and limitations

The main strength of this review is the combination of explanatory variables of all 24-h movement behaviors in people with prediabetes and people with T2D. To our knowledge, a systematic review combining the explanatory variables of these three behaviors has never been published, although this information is of utmost importance for the development of future interventions. Furthermore, studies were only included when objective measurement methods were used, which limits findings based on recall bias and over- and underestimation due to the use of subjective measurement methods (i.e. self-reported measures such as questionnaires or diaries) [132,133]. According to the Joanna Briggs Institute appraisal checklist for analytical cross-sectional studies, most of the studies included in this review had a low risk of bias.

Some limitations of this systematic review need to be acknowledged. High heterogeneity in the conceptualization of the objective measures of PA, SB and sleep was observed (e.g. total energy expenditure, steps/day). This might hamper comparison within the five behavioral categories that were created (i.e. sleep duration, SB, LPA, MVPA, total PA). Furthermore, due to the exclusion of self-reports we might have missed additional research about explanatory variables because self-reports are often used to measure movement behaviors. Next, given the large dispersion of the investigated explanatory variables, all variables were included even if they were investigated only once. However, we interpreted the results only when an explanatory variable was investigated at least two times in two independent studies. In some studies, the results were reported separately for specific subgroups (e.g. results reported for ages ≤58 years and ages ≥59 years [57]) and these were included separately in the evidence tables. This implies that subgroup results were considered separate studies which might impact the conclusion on the strength and/or direction of the associations. Given the diversity in the conceptualization of behavioral outcomes and explanatory variables which were often investigated once, no meta-analysis was conducted. Finally, the majority of the included studies were cross-sectional and involved limited information about causal interference.

5. Conclusion

Until now, the majority of studies have reported explanatory variables primarily situated at the intrapersonal level of the SEM, indicating a trend where 24-h movement behaviors tend to be less optimal with increasing age. Moreover, men with T2D appear to allocate more time to MVPA but less time to LPA than women with T2D. Notably, studies addressing explanatory variables at the interpersonal and environmental levels are rare, highlighting the absence of the socio-ecological approach toward understanding the reasons for behaving during a 24-h day. Given the known favorable impact of optimal 24-h movement behaviors on health outcomes, there is a need for additional evidence regarding explanatory variables across all socio-ecological levels, with particular emphasis on sleep and LPA. Nevertheless, the information gathered in this review provides some recommendations for the development of future interventions targeting 24-h movement behaviors in people with prediabetes and T2D.

Contribution statement

I. Willems, M. De Craemer and V. Verbestel conceived the initial idea for this review. I. Willems and V. Verbestel designed the protocol and collected the data. I. Willems, L. Bogaert, M. Kinaupenne, M. Decraene, B. Strumane, M. Van Daele, V. Verbestel and M. De Craemer analyzed the data. L. Bogaert, M. De Craemer and V. Verbestel wrote the manuscript. All authors reviewed and approved the final version of the manuscript.

Funding

Iris Willems was funded by Research Foundation Flanders (Fonds voor Wetenschappelijk Onderzoek), grant number 11N0422N.

Data availability

All the data generated or analyzed during this study are included in this published article and its supplementary information files.

Declaration of competing interest

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

Acknowledgement

Not applicable.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.dsx.2024.102995.

References

[1] Jadhav RA, Hazari A, Monterio A, Kumar S, Maiya AG. Effect of physical activity intervention in prediabetes: a systematic review with meta-analysis. J Phys Activ Health 2017;14(9):745–55. https://doi.org/10.1123/jpah.2016-0632.
[2] Hostalek U. Global epidemiology of prediabetes - present and future perspectives. Cli Diab Endocrinol 2019;5(1):5. https://doi.org/10.1186/s40842-019-0080-0.
[3] Roden M, Shulman GI. The integrative biology of type 2 diabetes. Nature 2019;576(7785):51–60. https://doi.org/10.1038/s41586-019-1797-8.
[4] Galicia-Garcia U, Benito-Vicente A, Jebari S, Larrea-Sebal A, Siddiqi H, Uribe KB, et al. Pathophysiology of type 2 diabetes mellitus. Int J Mol Sci [Internet] 2020;21(17).
[5] IDF Diabetes Atlas. The international diabetes federation. 2021.
[6] Zheng Y, Ley SH, Hu FB. Global aetiology and epidemiology of type 2 diabetes mellitus and its complications. Nat Rev Endocrinol 2018;14(2):88–98. https://doi.org/10.1038/nrendo.2017.151.
[7] Pfeiffer AF, Klein HH. The treatment of type 2 diabetes. Dtsch Arztebl Int 2014;111(5):69–81. https://doi.org/10.3238/arztebl.2014.0069.
[8] Biuso TJ, Butterworth S, Linden A. A conceptual framework for targeting prediabetes with lifestyle, clinical, and behavioral management interventions. Dis Manag 2007;10(1):6–15. https://doi.org/10.1089/dis.2006.628.
[9] Tuso P. Prediabetes and lifestyle modification: time to prevent a preventable disease. Perm J 2014;18(3):88–93. https://doi.org/10.7812/tpp/14-002.
[10] Davies MJ, Aroda VR, Collins BS, Gabbay RA, Green J, Maruthur NM, et al. Management of hyperglycaemia in type 2 diabetes, 2022. A consensus report by the American diabetes association (ADA) and the European association for the study of diabetes (EASD). Diabetologia 2022;65(12):1925–66. https://doi.org/10.1007/s00125-022-05787-2.
[11] Swindell N, Rees P, Fogelholm M, Drummen M, MacDonald I, Martinez JA, et al. Compositional analysis of the associations between 24-h movement behaviours and cardio-metabolic risk factors in overweight and obese adults with pre-diabetes from the PREVIEW study. Int J Behav Nutr Phys Activ 2020;17(1):29. https://doi.org/10.1186/s12966-020-00936-5.
[12] Rossen J, Buman MP, Johansson UB, Yngve A, Ainsworth B, Brismar K, et al. Reallocating bouted sedentary time to non-bouted sedentary time, light activity and moderate-vigorous physical activity in adults with prediabetes and type 2 diabetes. PLoS One 2017;12(7). https://doi.org/10.1371/journal.pone.0181053.
[13] Willems I, Verbestel V, Dumuid D, Stanford TE, Calders P, Lapauw B, et al. Cross-sectional associations between 24-hour movement behaviors and cardiometabolic health among adults with type 2 diabetes mellitus: a comparison according to weight status. J Sci Med Sport 2023. https://doi.org/10.1016/j.jsams.2023.11.010.
[14] Hajna S, Kestens Y, Daskalopoulou SS, Joseph L, Thierry B, Sherman M, et al. Neighbourhood walkability and home neighbourhood-based physical activity: an observational study of adults with type 2 diabetes. BMC Publ Health 2016;16(1):957. https://doi.org/10.1186/s12889-016-3603-y.
[15] Morowatisharifabad MA, Abdolkarimi M, Asadpour M, Fathollahi MS, Balaee P. Study on social support for exercise and its impact on the level of physical activity of patients with type 2 diabetes. Open Access Maced J Med Sci 2019;7(1):143–7. https://doi.org/10.3889/oamjms.2019.016.
[16] Sallis JF, Cervero RB, Ascher W, Henderson KA, Kraft MK, Kerr J. An ecological approach to creating active living communities. Annu Rev Publ Health 2006;27:297–322. https://doi.org/10.1146/annurev.publhealth.27.021405.102100.
[17] Stokols D. Translating social ecological theory into guidelines for community health promotion. Am J Health Promot 1996;10(4):282–98. https://doi.org/10.4278/0890-1171-10.4.282.
[18] Townsend N, Foster C. Developing and applying a socio-ecological model to the promotion of healthy eating in the school. Publ Health Nutr 2013;16(6):1101–8. https://doi.org/10.1017/S1368980011002655.
[19] Jackson SF, Perkins F, Khandor E, Cordwell L, Hamann S, Buasai S. Integrated health promotion strategies: a contribution to tackling current and future health challenges. Health Promot Int 2006;21(Suppl 1):75–83. https://doi.org/10.1093/heapro/dal054.
[20] Wold B, Mittelmark MB. Health-promotion research over three decades: the social-ecological model and challenges in implementation of interventions. Scand J Publ Health 2018;46(20):20–6. https://doi.org/10.1177/1403494817743893.
[21] Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021;372:71. https://doi.org/10.1136/bmj.n71.
[22] Checklist for analytical cross sectional studies. The Joanna Briggs Institute; 2017.
[23] Meeus M, Gebruers N. Health literacy : from reference to review: Leuven : Acco. 2016.
[24] Sallis JF, Prochaska JJ, Taylor WC. A review of correlates of physical activity of children and adolescents. Med Sci Sports Exerc 2000;32(5):963–75. https://doi.org/10.1097/00005768-200005000-00014.
[25] Hinkley T, Crawford D, Salmon J, Okely AD, Hesketh K. Preschool children and physical activity: a review of correlates. Am J Prev Med 2008;34(5):435–41. https://doi.org/10.1016/j.amepre.2008.02.001.
[26] Hinkley T, Salmon J, Okely AD, Trost SG. Correlates of sedentary behaviours in preschool children: a review. Int J Behav Nutr Phys Activ 2010;7(1):66. https://doi.org/10.1186/1479-5868-7-66.
[27] Chasens ER, Yang K. Insomnia and physical activity in adults with prediabetes. Clin Nurs Res 2012;21(3):294–308. https://doi.org/10.1177/1054773811411295.
[28] Kariuki JK, Rockette-Wagner B, Cheng J, Erickson KI, Gibbs BB, Sereika SM, et al. Neighborhood walkability is associated with physical activity and prediabetes in a behavioral weight loss study: a secondary analysis. Int J Behav Med 2022.
[29] Reutrakul S, Sumritsopak R, Saetung S, Chanprasertyothin S, Chailurkit LO, Anothaisintawee T. Lower nocturnal urinary 6-sulfatoxymelatonin is associated with more severe insulin resistance in patients with prediabetes. Neurobiol Sleep Circadian Rhythms 2018;4:10–6. https://doi.org/10.1016/j.nbscr.2017.06.001.
[30] Steeves JA, Murphy RA, Crainiceanu CM, Zipunnikov V, Van Domelen DR, Harris TB. Daily patterns of physical activity by type 2 diabetes definition: comparing diabetes, prediabetes, and participants with normal glucose levels in NHANES 2003–2006. Prevent Med Rep 2015;2:152–7. https://doi.org/10.1016/j.pmedr.2015.02.007.
[31] Swindell N, Mackintosh K, McNarry M, Stephens JW, Sluik D, Fogelholm M, et al. Objectively measured physical activity and sedentary time are associated with cardiometabolic risk factors in adults with prediabetes: the PREVIEW study. Diabetes Care 2018;41(3):562–9. https://doi.org/10.2337/dc17-1057.
[32] Yates T, Davies M, Gorely T, Bull F, Khunti K. Rationale, design and baseline data from the Pre-diabetes Risk Education and Physical Activity Recommendation and Encouragement (PREPARE) programme study: a randomized controlled trial. Patient Educ Counsel 2008;73(2):264–71. https://doi.org/10.1016/j.pec.2008.06.010.
[33] Yates T, Henson J, Khunti K, Morris DH, Edwardson C, Brady E, et al. Effect of physical activity measurement type on the association between walking activity and glucose regulation in a high-risk population recruited from primary care. Int J Epidemiol 2013;42(2):533–40. https://doi.org/10.1093/ije/dyt015.
[34] Alghamdi AS, Alghamdi KA, Jenkins RO, Alghamdi MN, Haris PI. Impact of ramadan on physical activity and sleeping patterns in individuals with type 2 diabetes: the first study using fitbit device. Diabetes Ther 2020;11(6):1331–46. https://doi.org/10.1007/s13300-020-00825-x.
[35] Alothman S, Alshehri MM, Alenazi AM, Rucker J, Kluding PM. The association between sedentary behavior and health variables in people with type 2 diabetes. Health Behav Pol Rev 2020;7(3):198–206. https://doi.org/10.14485/HBPR.7.3.4.
[36] Alshehri MM, Alkathiry AA, Alenazi AM, Alothman SA, Rucker JL, Phadnis MA, et al. Sleep efficiency and total sleep time in individuals with type 2 diabetes with and without insomnia symptoms. Sleep Disord 2020:5950375. 20200717 ed.
[37] An KH, Han KA, Sohn TS, Park IB, Kim HJ, Moon SD, et al. Body fat is related to sedentary behavior and light physical activity but not to moderate-vigorous physical activity in type 2 diabetes mellitus. Diabetes Metab J 2020;44(2):316–25. https://doi.org/10.4093/dmj.2019.0029.
[38] Baier JM, Funck KL, Vernstrøm L, Laugesen E, Poulsen PL. Low physical activity is associated with impaired endothelial function in patients with type 2 diabetes

and controls after 5 years of follow-up. BMC Endocr Disord 2021;21(1):189. https://doi.org/10.1186/s12902-021-00857-9.
[39] Balducci S, D'Errico V, Haxhi J, Sacchetti M, Orlando G, Cardelli P, et al. Level and correlates of physical activity and sedentary behavior in patients with type 2 diabetes: a cross-sectional analysis of the Italian Diabetes and Exercise Study_2. PLoS One 2017;12(3). https://doi.org/10.1371/journal.pone.0173337.
[40] Bazargan-Hejazi S, Arroyo JS, Hsia S, Brojeni NR, Pan D. A racial comparison of differences between self-reported and objectively measured physical activity among US adults with diabetes. Ethn Dis 2017;27(4):403–10. https://doi.org/10.18865/ed.27.4.403.
[41] Bermudez-Millan A, Schumann KP, Feinn R, Tennen H, Wagner J. Behavioral reactivity to acute stress among Black and White women with type 2 diabetes: the roles of income and racial discrimination. J Health Psychol 2016;21(9):2085–97. https://doi.org/10.1177/1359105315571776.
[42] Bevier W, Glantz N, Hoppe C, Morales Glass J, Larez A, Chen K, et al. Self-reported and objectively measured physical activity levels among Hispanic/Latino adults with type 2 diabetes. BMJ Open Diabetes Res Care 2020;8(1). https://doi.org/10.1136/bmjdrc-2019-000893.
[43] Bjørgaas M, Vik JT, Saeterhaug A, Langlo L, Sakshaug T, Mohus RM, et al. Relationship between pedometer-registered activity, aerobic capacity and self-reported activity and fitness in patients with type 2 diabetes. Diabetes Obes Metabol 2005;7(6):737–44. https://doi.org/10.1111/j.1463-1326.2004.00464.x.
[44] Booth JE, Leung AA, Benham JL, Rabi DM, Goldfield GS, Sajobi T, et al. Sociodemographic factors associated with objectively measured moderate- to vigorous-intensity physical activity in adults with type 2 diabetes: cross-sectional results from the Canadian health measures survey (2007 to 2017). Can J Diabetes 2022;46(6):578–85. https://doi.org/10.1016/j.jcjd.2022.04.001.
[45] Braver NRd, Rutters F, Wagtendonk AJ, Kok JG, Harms PP, Brug J, et al. Neighborhood walkability, physical activity and changes in glycemic markers in people with type 2 diabetes: the Hoorn Diabetes Care System cohort. Health Place 2021:102560. 20210321 ed.
[46] Castonguay A, Miquelon P. Motivational profiles, accelerometer-derived physical activity, and acute diabetes-related symptoms in adults with type 2 diabetes. BMC Publ Health 2018;18(1):469. https://doi.org/10.1186/s12889-018-5376-y.
[47] Chlebowy DO, Kubiak N, Myers J, Jorayeva A. The relationships of demographic characteristics with diabetes biomarkers and physical activity adherence in African American adults. J Racial Ethn Health Disparities 2016;3(2):240–4. https://doi.org/10.1007/s40615-015-0133-8.
[48] Cooper AR, Sebire S, Montgomery AA, Peters TJ, Sharp DJ, Jackson N, et al. Sedentary time, breaks in sedentary time and metabolic variables in people with newly diagnosed type 2 diabetes. Diabetologia 2012;55(3):589–99. https://doi.org/10.1007/s00125-011-2408-x.
[49] Cooper AJ, Brage S, Ekelund U, Wareham NJ, Griffin SJ, Simmons RK. Association between objectively assessed sedentary time and physical activity with metabolic risk factors among people with recently diagnosed type 2 diabetes. Diabetologia 2014;57(1):73–82. https://doi.org/10.1007/s00125-013-3069-8.
[50] Dasgupta K, Rosenberg E, Joseph L, Trudeau L, Garfield N, Chan D, et al. Carotid femoral pulse wave velocity in type 2 diabetes and hypertension: capturing arterial health effects of step counts. J Hypertens 2017;35(5):1061–9. https://doi.org/10.1097/hjh.0000000000001277.
[51] Dauriz M, Bacchi E, Boselli L, Santi L, Negri C, Trombetta M, et al. Association of free-living physical activity measures with metabolic phenotypes in type 2 diabetes at the time of diagnosis. The Verona Newly Diagnosed Type 2 Diabetes Study (VNDS). Nutr Metabol Cardiovasc Dis 2018;28(4):343–51. https://doi.org/10.1016/j.numecd.2017.12.011.
[52] De Greef K, Van Dyck D, Deforche B, De Bourdeaudhuij I. Physical environmental correlates of self-reported and objectively assessed physical activity in Belgian type 2 diabetes patients. Health Soc Care Community 2011;19(2):178–88. https://doi.org/10.1111/j.1365-2524.2010.00958.x.
[53] Ding S, Zhang P, Wang L, Wang D, Sun K, Ma Y, et al. Prevalence of obstructive sleep apnea syndrome in hospitalized patients with type 2 diabetes in Beijing, China. J Diabetes Invest 2022;13(11):1889–96. https://doi.org/10.1111/jdi.13868.
[54] Falconer CL, Cooper AR, Walhin JP, Thompson D, Page AS, Peters TJ, et al. Sedentary time and markers of inflammation in people with newly diagnosed type 2 diabetes. Nutr Metabol Cardiovasc Dis 2014;24(9):956–62. https://doi.org/10.1016/j.numecd.2014.03.009.
[55] Foster GD, Sanders MH, Millman R, Zammit G, Borradaile KE, Newman AB, et al. Obstructive sleep apnea among obese patients with type 2 diabetes. Diabetes Care 2009;32(6):1017–9. https://doi.org/10.2337/dc08-1776.
[56] Fritschi C, Park H, Richardson A, Park C, Collins EG, Mermelstein R, et al. Association between daily time spent in sedentary behavior and duration of hyperglycemia in type 2 diabetes. Biol Res Nurs 2016;18(2):160–6. https://doi.org/10.1177/1099800415600065.
[57] Fritschi C, Bronas UG, Park CG, Collins EG, Quinn L. Early declines in physical function among aging adults with type 2 diabetes. J Diabet Complicat 2017;31(2):347–52. https://doi.org/10.1016/j.jdiacomp.2016.06.022.
[58] Guo VY, Brage S, Ekelund U, Griffin SJ, Simmons RK. Objectively measured sedentary time, physical activity and kidney function in people with recently diagnosed Type 2 diabetes: a prospective cohort analysis. Diabet Med 2016;33(9):1222–9. https://doi.org/10.1111/dme.12886.
[59] Helgeson VS, Naqvi JB, Korytkowski MT, Gary-Webb TL. A closer look at racial differences in diabetes outcomes among a community sample: diabetes distress, self-care, and HbA(1c). Diabetes Care 2021;44(11):2487–92. https://doi.org/10.2337/dc21-0734.
[60] Henson J, Rowlands AV, Baldry E, Brady EM, Davies MJ, Edwardson CL, et al. Physical behaviors and chronotype in people with type 2 diabetes. BMJ Open Diabetes Res Care 2020;8(1). https://doi.org/10.1136/bmjdrc-2020-001375.
[61] Imam A, Winnebeck EC, Buchholz N, Froguel P, Bonnefond A, Solimena M, et al. Circadian, sleep and caloric intake phenotyping in type 2 diabetes patients with rare melatonin receptor 2 mutations and controls: a pilot study. Front Physiol 2020:564140. 20201009 ed.
[62] Kajbaf F, Fendri S, Basille-Fantinato A, Diouf M, Rose D, Jounieaux V, et al. The relationship between metformin therapy and sleep quantity and quality in patients with Type 2 diabetes referred for potential sleep disorders. Diabet Med 2014;31(5):577–80. https://doi.org/10.1111/dme.12362.
[63] Kaur K, Sandhu J. Analysis of physical activity patterns among type-2 diabetes mellitus: a cross-sectional study. Int J Physiother 2015;2:392. https://doi.org/10.15621/ijphy/2015/v2i2/65248.
[64] Kelly J, Edney K, Moran C, Srikanth V, Callisaya M. Gender differences in physical activity levels of older people with type 2 diabetes mellitus. J Phys Activ Health 2016;13(4):409–15. https://doi.org/10.1123/jpah.2015-0147.
[65] Lam DC, Lui MM, Lam JC, Ong LH, Lam KS, Ip MS. Prevalence and recognition of obstructive sleep apnea in Chinese patients with type 2 diabetes mellitus. Chest 2010;138(5):1101–7. https://doi.org/10.1378/chest.10-0596.
[66] Lamb MJE, Westgate K, Brage S, Ekelund U, Long GH, Griffin SJ, et al. Prospective associations between sedentary time, physical activity, fitness and cardiometabolic risk factors in people with type 2 diabetes. Diabetologia 2016;59(1):110–20. https://doi.org/10.1007/s00125-015-3756-8.
[67] Manyara AM, Mwaniki E, Gray CM, Gill JMR. Comparison of risk factors between people with type 2 diabetes and matched controls in Nairobi, Kenya. Trop Med Int Health 2021;26(9):1075–87. https://doi.org/10.1111/tmi.13629.
[68] Mathe N, Boyle T, Al Sayah F, Mundt C, Vallance JK, Johnson JA, et al. Correlates of accelerometer-assessed physical activity and sedentary time among adults with type 2 diabetes. Can J Public Health 2017;108(4):355–61. https://doi.org/10.17269/cjph.108.5954.
[69] McMillan KA, Paing AC, Kirk AF, Hewitt A, MacRury S, Collier A, et al. Measuring group and individual relationship between patterns in sedentary behaviour and glucose in type 2 diabetes adults. Practical Diabetes 2020;37(1):13–8. https://doi.org/10.1002/pdi.2254.
[70] Morris JL, Sereika SM, Houze M, Chasens ER. Effect of nocturia on next-day sedentary activity in adults with type 2 diabetes. Appl Nurs Res 2016;32:44–6. https://doi.org/10.1016/j.apnr.2016.04.006.
[71] Paing AC, McMillan KA, Kirk AF, Collier A, Hewitt A, Dunstan D, et al. Diurnal patterns of objectively measured sedentary time and interruptions to sedentary time are associated with glycaemic indices in type 2 diabetes. J Sci Med Sport 2020;23(11):1074–9. https://doi.org/10.1016/j.jsams.2020.06.003.
[72] Pezzino S, Florenty S, Fagour C, Gin H, Rigalleau V. Remedial actions for the physical inactivity of hospitalized patients with type 2 diabetes. Diabetes Care 2010;33(9):1960–1. https://doi.org/10.2337/dc10-0806.
[73] Phillips LA, Cohen J, Burns E, Abrams J, Renninger S. Self-management of chronic illness: the role of 'habit' versus reflective factors in exercise and medication adherence. J Behav Med 2016;39(6):1076–91. https://doi.org/10.1007/s10865-016-9732-z.
[74] Pizzol D, Smith L, Koyanagi A, Stubbs B, Grabovac I, Jackson SE, et al. Do older people with diabetes meet the recommended weekly physical activity targets? An analysis of objective physical activity data. Int J Environ Res Publ Health 2019;16(14). https://doi.org/10.3390/ijerph16142489.
[75] Plotnikoff RC, Karunamuni N, Courneya KS, Sigal RJ, Johnson JA, Johnson ST. The Alberta Diabetes and Physical Activity Trial (ADAPT): a randomized trial evaluating theory-based interventions to increase physical activity in adults with type 2 diabetes. Ann Behav Med 2013;45(1):45–56. https://doi.org/10.1007/s12160-012-9405-2.
[76] Poppe L, De Paepe AL, Van Ryckeghem DML, Van Dyck D, Maes I, Crombez G. The impact of mental and somatic stressors on physical activity and sedentary behaviour in adults with type 2 diabetes mellitus: a diary study. PeerJ 2021;9. https://doi.org/10.7717/peerj.11579.
[77] Preiss D, Haffner SM, Thomas LE, Sun JL, Sattar N, Yates T, et al. Change in levels of physical activity after diagnosis of type 2 diabetes: an observational analysis from the NAVIGATOR study. Diabetes Obes Metabol 2014;16(12):1265–8. https://doi.org/10.1111/dom.12320.
[78] Preiss D, Thomas LE, Wojdyla DM, Haffner SM, Gill JMR, Yates T, et al. Prospective relationships between body weight and physical activity: an observational analysis from the NAVIGATOR study. BMJ Open 2015;5(8). https://doi.org/10.1136/bmjopen-2015-007901.
[79] Pupier E, Fagour C, Tavitian M, Pezzino S, Rigalleau V. Physical activity levels of patients with type 2 diabetes in hospital and at home. Acta Diabetol 2018;55(1):107–9. https://doi.org/10.1007/s00592-017-1067-x.
[80] Reutrakul S, Crowley SJ, Park JC, Chau FY, Priyadarshini M, Hanlon EC, et al. Relationship between intrinsically photosensitive ganglion cell function and circadian regulation in diabetic retinopathy. Sci Rep 2020;10(1):1560. https://doi.org/10.1038/s41598-020-58205-1.
[81] Rowlands AV, Henson JJ, Coull NA, Edwardson CL, Brady E, Hall A, et al. The impact of COVID-19 restrictions on accelerometer-assessed physical activity and sleep in individuals with type 2 diabetes. Diabet Med 2021;38(10). https://doi.org/10.1111/dme.14549.
[82] Sardinha LB, Magalhães JP, Santos DA, Júdice PB. Sedentary patterns, physical activity, and cardiorespiratory fitness in association to glycemic control in type 2 diabetes patients. Front Physiol 2017;8:262. https://doi.org/10.3389/fphys.2017.00262.

[83] Siddiqui MA, Bhana S, Daya R. The relationship between objectively measured physical activity and parameters of disease control in an African population of type 2 diabetes mellitus. J Endocrinol Metabol Diabetes S Afr 2018;23(3):80–5. https://doi.org/10.1080/16089677.2018.1515144.
[84] Sirisreetreerux S, Sujirakul T, Nimitphong H, Pinyopodjanard S, Saetung S, Chailurkit LO, et al. Sleep variability, 6-sulfatoxymelatonin, and diabetic retinopathy. Sleep Breath 2021;25(2):1069–74. https://doi.org/10.1007/s11325-020-02165-3.
[85] Strycker L, Duncan S, Chaumeton N, Duncan T, Toobert D. Reliability of pedometer data in samples of youth and older women. Int J Behav Nutr Phys Activ 2007;4:4. https://doi.org/10.1186/1479-5868-4-4.
[86] Tudor-Locke CE, Bell RC, Myers AM, Harris SB, Lauzon N, Rodger NW. Pedometer-determined ambulatory activity in individuals with type 2 diabetes. Diabetes Res Clin Pract 2002;55(3):191–9. https://doi.org/10.1016/s0168-8227(01)00317-5.
[87] Weatherall J, Paprocki Y, Meyer TM, Kudel I, Witt EA. Sleep tracking and exercise in patients with type 2 diabetes mellitus (Step-D): pilot study to determine correlations between fitbit data and patient-reported outcomes. JMIR Mhealth Uhealth 2018;6(6):131. https://doi.org/10.2196/mhealth.8122.
[88] Whitaker KM, Lutsey PL, Ogilvie RP, Pankow JS, Bertoni A, Michos ED, et al. Associations between polysomnography and actigraphy-based sleep indices and glycemic control among those with and without type 2 diabetes: the Multi-Ethnic Study of Atherosclerosis. Sleep 2018;41(11). https://doi.org/10.1093/sleep/zsy172.
[89] Zabetian-Targhi F, Srikanth VK, Beare R, Breslin M, Moran C, Wang W, et al. The association between physical activity intensity, cognition, and brain structure in people with type 2 diabetes. J Gerontol A Biol Sci Med Sci 2021;76(11):2047–53. https://doi.org/10.1093/gerona/glab067.
[90] Zhu B, Chen P, Kim MJ, Chen X, Quinn L, Fritschi C. Fluctuations in self-reported symptoms predict objective physical activity in adults with type 2 diabetes. Sci Diabetes Self Manag Care 2021;47(4):255–63. https://doi.org/10.1177/26350106211015889.
[91] Zucatti ATN, de Paula TP, Viana LV, DallAgnol R, Cureau FV, Azevedo MJ, et al. Low levels of usual physical activity are associated with higher 24 h blood pressure in type 2 diabetes mellitus in a cross-sectional study. J Diabetes Res 2017;2017. https://doi.org/10.1155/2017/6232674.
[92] Hein M, Lanquart J-P, Mungo A, Loas G. Cardiovascular risk associated with co-morbid insomnia and sleep apnoea (COMISA) in type 2 diabetics. Sleep Sci 2022; 15(2022).
[93] Jakicic JM, Gregg E, Knowler W, Kelley DE, Lang W, Miller GD, et al. Activity patterns of obese adults with type 2 diabetes in the look AHEAD study. Med Sci Sports Exerc 2010;42(11):1995–2005. https://doi.org/10.1249/MSS.0b013e3181e054f0.
[94] Johnson ST, Thiel D, Al Sayah F, Mundt C, Qiu W, Buman MP, et al. Objectively measured sleep and health-related quality of life in older adults with type 2 diabetes: a cross-sectional study from the Alberta's Caring for Diabetes Study. Sleep Health 2017;3(2):102–6. https://doi.org/10.1016/j.sleh.2016.12.002.
[95] Hamasaki H, Kawashima Y, Adachi H, Moriyama S, Katsuyama H, Sako A, et al. Associations between lower extremity muscle mass and metabolic parameters related to obesity in Japanese obese patients with type 2 diabetes. PeerJ 2015;3:942. https://doi.org/10.7717/peerj.942.
[96] Colomer FA, Cugat MÀC, Bort-Roig J, Chirveches-Pérez E, Zaldúa YC, Martín-Cantera C, et al. Differences in free-living patterns of sedentary behaviour between office employees with diabetes and office employees without diabetes: a principal component analysis for clinical practice. Int J Environ Res Publ Health 2022;19(19). https://doi.org/10.3390/ijerph191912245.
[97] Lee DY, Kim N, Jung I, Park SY, Yu JH, Seo JA, et al. Clinical and lifestyle determinants of continuous glucose monitoring metrics in insulin-treated patients with type 2 diabetes mellitus. Diabetes Metab J 2023. https://doi.org/10.4093/dmj.2022.0273.
[98] Magri CJ, Xuereb S, Xuereb RA, Xuereb RG, Fava S, Galea J. Sleep measures and cardiovascular disease in type 2 diabetes mellitus. Clin Med 2023. https://doi.org/10.7861/clinmed2022-0442.
[99] Rowlands AV, van Hees VT, Dawkins NP, Maylor BD, Plekhanova T, Henson J, et al. Accelerometer-assessed physical activity in people with type 2 diabetes: accounting for sleep when determining associations with markers of health. Sensors 2023;23(12). https://doi.org/10.3390/s23125382.
[100] De Man J, Wouters E, Absetz P, Daivadanam M, Naggayi G, Kasujja FX, et al. What motivates people with (Pre)Diabetes to move? Testing self-determination theory in rural Uganda. Front Psychol 2020;11. https://doi.org/10.3389/fpsyg.2020.00404.
[101] Hamasaki H, Noda M, Moriyama S, Yoshikawa R, Katsuyama H, Sako A, et al. Daily physical activity assessed by a triaxial accelerometer is beneficially associated with waist circumference, Serum triglycerides, and insulin resistance in Japanese patients with prediabetes or untreated early type 2 diabetes. J Diabetes Res 2015;2015. https://doi.org/10.1155/2015/526201.
[102] Mokhlesi B, Tjaden AH, Temple KA, Edelstein SL, Sam S, Nadeau KJ, et al. Obstructive sleep apnea, glucose tolerance, and β-cell function in adults with prediabetes or untreated type 2 diabetes in the restoring insulin secretion (RISE) study. Diabetes Care 2021;44(4):993–1001. https://doi.org/10.2337/dc20-2127.
[103] Rockette-Wagner B, Storti KL, Dabelea D, Edelstein S, Florez H, Franks PW, et al. Activity and sedentary time 10 Years after a successful lifestyle intervention: the diabetes prevention program. Am J Prev Med 2017;52(3):292–9. https://doi.org/10.1016/j.amepre.2016.10.007.
[104] Dzakpasu FQS, Koster A, Owen N, Galan BE, Carver A, Brakenridge CJ, et al. Device-measured sitting time and musculoskeletal pain in adults with normal glucose metabolism, prediabetes and type 2 diabetes-The Maastricht Study. PLoS One 2023;18(5):e0285276. https://doi.org/10.1371/journal.pone.0285276.
[105] Steeves JA, Murphy RA, Crainiceanu CM, Zipunnikov V, Van Domelen DR, Harris TB. Daily patterns of physical activity by type 2 diabetes definition: comparing diabetes, prediabetes, and participants with normal glucose levels in NHANES 2003-2006. Prev Med Rep 2015;2:152–7. https://doi.org/10.1016/j.pmedr.2015.02.007.
[106] Lee DY, Kim N, Jung I, Park SY, Yu JH, Seo JA, et al. Clinical and lifestyle determinants of continuous glucose monitoring metrics in insulin-treated patients with type 2 diabetes. Diabetes 2023;72. https://doi.org/10.2337/db23-975-P.
[107] Rowlands AV, van Hees VT, Dawkins NP, Maylor BD, Plekhanova T, Henson J, et al. Accelerometer-assessed physical activity in people with type 2 diabetes: accounting for sleep when determining associations with markers of health. Sensors 2023;23(12):5382.
[108] Ottowa charter for health promotion. Geneva: World Health Organization; 1986.
[109] Simon C, Kellou N, Dugas J, Platat C, Copin N, Schweitzer B, et al. A socio-ecological approach promoting physical activity and limiting sedentary behavior in adolescence showed weight benefits maintained 2.5 years after intervention cessation. Int J Obes 2014;38(7):936–43. https://doi.org/10.1038/ijo.2014.23.
[110] Kellou N, Sandalinas F, Copin N, Simon C. Prevention of unhealthy weight in children by promoting physical activity using a socio-ecological approach: what can we learn from intervention studies? Diabetes Metab 2014;40(4):258–71. https://doi.org/10.1016/j.diabet.2014.01.002.
[111] Noh W, Kim KY. Review of ecological approach factors affecting physical activity among older people. West J Nurs Res 2022;44(8):799–808. https://doi.org/10.1177/01939459211017530.
[112] Cochrane T, Davey RC. Increasing uptake of physical activity: a social ecological approach. J R Soc Promot Health 2008;128(1):31–40. https://doi.org/10.1177/1466424007085223.
[113] Grandner M. Addressing sleep disturbances: an opportunity to prevent cardiometabolic disease? Int Rev Psychiatr 2014;26. https://doi.org/10.3109/09540261.2014.911148.
[114] Habibi Soola A, Davari M, Rezakhani Moghaddam H. Determining the predictors of self-management behaviors in patients with type 2 diabetes: an application of socio-ecological approach. Front Public Health 2022;10. https://doi.org/10.3389/fpubh.2022.820238.
[115] Donat Tuna H, Ozcan Edeer A, Malkoc M, Aksakoglu G. Effect of age and physical activity level on functional fitness in older adults. Europ Rev Aging Phys Activ 2009;6(2):99. https://doi.org/10.1007/s11556-009-0051-z.
[116] Suorsa K, Leskinen T, Pasanen J, Pulakka A, Myllyntausta S, Pentti J, et al. Changes in the 24-h movement behaviors during the transition to retirement: compositional data analysis. Int J Behav Nutr Phys Activ 2022;19(1):121. https://doi.org/10.1186/s12966-022-01364-3.
[117] Kaplan MS, Newsom JT, McFarland BH, Lu L. Demographic and psychosocial correlates of physical activity in late life. Am J Prev Med 2001;21(4):306–12. https://doi.org/10.1016/S0749-3797(01)00364-6.
[118] Rhodes RE, Mark RS, Temmel CP. Adult sedentary behavior: a systematic review. Am J Prev Med 2012;42(3):3–28. https://doi.org/10.1016/j.amepre.2011.10.020.
[119] Jefferis BJ, Sartini C, Lee IM, Choi M, Amuzu A, Gutierrez C, et al. Adherence to physical activity guidelines in older adults, using objectively measured physical activity in a population-based study. BMC Publ Health 2014;14(1):382. https://doi.org/10.1186/1471-2458-14-382.
[120] Westerterp KR. Changes in physical activity over the lifespan: impact on body composition and sarcopenic obesity. Obes Rev 2018;19:8–13. https://doi.org/10.1111/obr.12781.
[121] Ferrari G, Alberico C, Drenowatz C, Kovalskys I, Gómez G, Rigotti A, et al. Prevalence and sociodemographic correlates of meeting the Canadian 24-hour movement guidelines among Latin american adults: a multi-national cross-sectional study. BMC Publ Health 2022;22(1):217. https://doi.org/10.1186/s12889-022-12613-2.
[122] Michie S, Johnston M, Francis J, Hardeman W, Eccles M. From theory to intervention: mapping theoretically derived behavioural determinants to behaviour change techniques. Appl Psychol 2008;57(4):660–80. https://doi.org/10.1111/j.1464-0597.2008.00341.x.
[123] Trost SG, Owen N, Bauman AE, Sallis JF, Brown W. Correlates of adults' participation in physical activity: review and update. Med Sci Sports Exerc 2002; 34(12).
[124] Humpel N, Owen N, Leslie E. Environmental factors associated with adults' participation in physical activity: a review. Am J Prev Med 2002;22(3):188–99. https://doi.org/10.1016/S0749-3797(01)00426-3.
[125] Owen N, Humpel N, Leslie E, Bauman A, Sallis JF. Understanding environmental influences on walking: review and research agenda. Am J Prev Med 2004;27(1):67–76. https://doi.org/10.1016/j.amepre.2004.03.006.
[126] Alvarez S, Coffey R, Algotar AM. Prediabetes. StatPearls. Treasure Island (FL; 2022.
[127] Füzéki E, Engeroff T, Banzer W. Health benefits of light-intensity physical activity: a systematic review of accelerometer data of the national health and nutrition examination survey (NHANES). Sports Med 2017;47(9):1769–93. https://doi.org/10.1007/s40279-017-0724-0.
[128] Chastin SFM, De Craemer M, De Cocker K, Powell L, Van Cauwenberg J, Dall P, et al. How does light-intensity physical activity associate with adult cardiometabolic health and mortality? Systematic review with meta-analysis of experimental and observational studies. Br J Sports Med 2019;53(6):370–6. https://doi.org/10.1136/bjsports-2017-097563.

[129] Chaput JP, Carson V, Gray CE, Tremblay MS. Importance of all movement behaviors in a 24 hour period for overall health. Int J Environ Res Publ Health 2014;11(12):12575–81. https://doi.org/10.3390/ijerph111212575.

[130] Ahmad E, Sargeant JA, Yates T, Webb DR, Davies MJ. Type 2 diabetes and impaired physical function: a growing problem. Diabetology 2022;3(1):30–45.

[131] Rollo S, Antsygina O, Tremblay MS. The whole day matters: understanding 24-hour movement guideline adherence and relationships with health indicators across the lifespan. J Sport Health Sci 2020;9(6):493–510. https://doi.org/10.1016/j.jshs.2020.07.004.

[132] Prince SA, Cardilli L, Reed JL, Saunders TJ, Kite C, Douillette K, et al. A comparison of self-reported and device measured sedentary behaviour in adults: a systematic review and meta-analysis. Int J Behav Nutr Phys Activ 2020;17(1):31. https://doi.org/10.1186/s12966-020-00938-3.

[133] Dyrstad SM, Hansen BH, Holme IM, Anderssen SA. Comparison of self-reported versus accelerometer-measured physical activity. Med Sci Sports Exerc 2014;46(1):99–106. https://doi.org/10.1249/MSS.0b013e3182a0595f.