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The temporal interplay between physical activity, emotional well-being, and health-related quality of life in individuals with recently diagnosed type 2 diabetes mellitus: a cross-lagged panel analysis

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ABSTRACT

Aims: We investigated longitudinal, bidirectional associations between objectively measured moderate to vigorous physical activity (MVPA), health-related quality of life (HRQoL), and emotional well-being (EWB) in individuals recently diagnosed with type 2 diabetes mellitus.
Methods: Participants were 972 adults. MVPA was assessed using accelerometry, HRQoL using the SF-12 (physical [PCS], mental [MCS]), and EWB using the WHO-5. A three-wave cross-lagged panel model tested associations, adjusting for age and sex.
Results: Baseline PCS predicted MVPA at 24 months ($\beta = 0.124$, $p < 0.001$), and PCS at 24 months predicted MVPA at 48 months ($\beta = 0.146$, $p < 0.001$). Baseline MCS predicted MVPA at 24 months ($\beta = 0.116$, $p = 0.001$), but not 48 months ($\beta = -0.016$, $p = 0.653$). Baseline EWB predicted MVPA at 24 months ($\beta = 0.080$, $p = 0.023$), but not 48 months ($\beta = 0.068$, $p = 0.058$). Baseline MVPA did not predict PCS at 24 months ($\beta = 0.038$, $p = 0.184$), but MVPA at 24 months predicted PCS at 48 months ($\beta = 0.065$, $p = 0.024$). MVPA did not predict MCS or EWB.
Conclusions: HRQoL and EWB predicted subsequent MVPA, whereas MVPA showed limited and inconsistent effects on later HRQoL or EWB.

1. Introduction

Individuals with diabetes have an increased risk of impaired health-related quality of life (HRQoL) compared to individuals without diabetes [1,2]. Approximately 20% of individuals with type 2 diabetes mellitus have elevated depression and anxiety symptoms, which complicates disease management and elevates morbidity and mortality risks [3–5]. While patient-reported outcome measures are commonly used to screen for depression [6], existing research has primarily focused on individuals with type 2 diabetes mellitus who have long disease duration or diabetes related complications. Consequently, little is known about the psychological distress experienced during the early post-diagnosis

Abbreviations: CCI, Charlson comorbidity index score; DD2, Danish Centre for Strategic Research in Type 2 diabetes; IDA, Specialist Supervised Individualised Treatment of New Clinically Diagnosed Type 2 Diabetes in General Practice; EWB, Emotional well-being; HRQoL, Health-related quality of life; MCS, Mental component summary; MVPA, Moderate to vigorous physical activity; PCS, Physical component summary; SF-12, 12-item Short-Form Health Survey; SEM, Structural equation model; WHO-5, World Health Organization Five Well-Being Index questionnaire.

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period [7]. This period is critical, as initial adaptation to the disease could influence long-term health outcomes. However, the psychological burden of diabetes can compromise adherence to lifestyle recommendations, such as physical activity [8–10]. Given the central role of psychological well-being in diabetes management [11], a deeper understanding of how emotional well-being (EWB), HRQoL and physical activity interact is essential.

HRQoL is a multidimensional, subjective, and dynamic construct encompassing physical, mental, emotional, and social aspects [12,13]. It is a core outcome in diabetes mellitus research and is often diminished in individuals with type 2 diabetes mellitus due to the combined physical and psychological burden of the disease [14–16]. Notably, physical activity has been identified as a cornerstone of type 2 diabetes mellitus management, contributing to not only improved glycaemic control but also reduced diabetes distress and improved HRQoL [14,15]. However, despite its well-established benefits, adherence to physical activity recommendations remains low as many individuals with type 2 diabetes mellitus struggle to meet the recommended 150 min of moderate-intensity or 75 min of vigorous-intensity aerobic activity per week, with adherence rates as low as 50% [17–19]. Psychological distress, fatigue, and low motivation are frequently identified as barriers [20,21], highlighting the need for a more nuanced understanding of the factors influencing physical activity engagement.

Despite the established link between physical activity and improved HRQoL, previous research has primarily focused on a unidirectional relationship, where physical activity improves HRQoL and reduces psychological distress [13,22]. However, evidence for a potential bidirectional association remains unclear, particularly in individuals recently diagnosed with type 2 diabetes mellitus. Conceptually, these relationships may be reciprocal, where mental health can influence physical activity engagement as much as physical activity can affect well-being [23]. Understanding this dynamic is crucial for optimising diabetes management.

By utilising accelerometer-based moderate to vigorous physical activity (MVPA) and well-established questionnaires of HRQoL and EWB, this study aims to test the hypothesis that there are bidirectional associations between MVPA levels and HRQoL and EWB in a large cohort of individuals recently diagnosed with type 2 diabetes mellitus.

2. Methods and materials

2.1. Study sample and population

In this study, we use data from a prospective, controlled, multicentre, open-label intervention study entitled “The Specialist Supervised Individualised Treatment of New Clinically Diagnosed Type 2 Diabetes in General Practice” (IDA) reported elsewhere [24]. The IDA study enrolled 1,172 individuals, who provided written informed consent to participate; all recruited from the Danish cohort “The Danish Centre for Strategic Research in Type 2 diabetes” (DD2) [25]. All participants were recently diagnosed with type 2 diabetes mellitus at baseline according to the criteria defined in the DD2. The inclusion criteria for IDA are: 1) patient at a general practitioner (GP) participating in the IDA study, 2) not diagnosed with Type 1 Diabetes, defined as age < 30 years at DD2 enrollment, fasting C-peptide < 300 pM, and Gad65-ab > 20 IU/ml, 3) life expectancy above 2 years, 4) no participation in other clinical trials, and 5) Willingness to provide written informed consent [24]. The inclusion period for the IDA study spanned from 2013 to 2018. Although the original IDA study was an intervention study, this is not expected to have affected the outcome of this present study as the intervention was to evaluate the effect of a new pharmacological treatment concept based on personalised treatment in general practice under specialist supervision.

EWB was assessed using the World Health Organization Five Well-Being Index questionnaire (WHO-5) [26] and HRQoL by the 12-item Short-Form Health Survey (SF-12), encompassing physical component summary (PCS) and mental component summary (MCS) scores [27]. Physical activity was assessed using Axivity AX3 accelerometers. In the present study, we included 972 participants who had at least one valid accelerometer-based measurement of physical activity and at least one valid questionnaire response for both the WHO-5 and the SF-12, obtained at baseline, 24 months, or 48 months, not necessarily at the same time point. Of these participants, 245 had both accelerometer-based measurements of physical activity and responses to both questionnaires at all three time points, and they are referred to as complete cases.

2.2. Ethics

The IDA study received ethical approval from the Regional Committee on Medical Health Ethics (Region of Southern Denmark, S-20120186), as well as from the Danish Data Protection Agency and the Danish Medicines Authority (journal no. 2012120204). This study was conducted in accordance with the principles outlined in the Helsinki Declaration.

2.3. Outcome and exposure

2.3.1. Physical activity

To objectively assess 24-hour physical activity levels and step count, participants were equipped with two tri-axial accelerometers (Axivity AX3, Newcastle, UK). One device was attached to the thigh, which primarily monitored step count and movement behaviours inferred from the acceleration signal and the angle of thigh inclination, and another was attached to the lower back, responsible for capturing data on the volume and intensity of physical activity [28,29]. The accelerometers were affixed directly on the skin by trained research staff at each clinical visit using waterproof tape to ensure secure attachment during all daily activities. The study participants were instructed to wear both accelerometers continuously for 10 days, including during water activities such as showering or swimming. To ensure robust data collection, we defined inclusion criteria for a valid physical activity registration as 1) a minimum of 22 h of daily wear time, (2) wear time on at least two weekdays (Monday to Friday), and (3) wear time on at least one weekend day (Saturday or Sunday). This exclusion process did not alter the final number of observations, as the initial inclusion criteria were still met.

MVPA was defined using age-specific cut points determined by the average intensity in counts at preferred walking speed for moderate and running equivalent to 60% of VO_{2max} for vigorous. These cut-points were derived from an internally conducted calibration study using established methods [30]. Physical activity estimates were reported as a weighted average, with a 5:2 ratio for weekdays and weekends. A detailed description of the methodology is given elsewhere [31].

2.3.2. Health-related quality of life and emotional well-being

HRQoL was assessed using the SF-12 health-status assessment tool [27], which evaluates physical and mental health over the past four weeks. An eight-dimension profile (physical functioning, role limitations due to physical problems, bodily pain, general health, vitality, social function, emotional problems, and mental health) constitutes a weighted average of the PCS and MCS scores [32]. We calculated a PCS (physical functioning, role-physical, bodily pain, and general health) and a MCS (vitality, social functioning, role-emotional, and mental health) score as previously described [32]. A MCS score below 42 suggests an elevated risk of depression, while a PCS score below 50 indicates potential physical impairment [32]. These scores collectively provide a comprehensive overview of the participants’ perceived physical and mental health.

EWB was assessed using the WHO-5 instrument [26], which asks respondents to rate the five positive statements: 1) I have felt cheerful and in good spirit, 2) I have felt calm and relaxed, 3) I have felt active and vigorous, 4) I woke up feeling fresh and rested, and 5) my daily life has been filled with things that interest me, applied to them in the past

14 days. This should be done on a 6-point Likert scale rating from "at no time" (0) to "all the time" (5). The raw score, which ranges from 0 (absent) to 25 (maximal well-being), is converted into a percentage scale by multiplying the raw score by 4, ranging from 0 (absent) to 100 (maximal), with higher values indicating greater EWB [33,34].

Both the MCS of the SF-12 and the EWB of the WHO-5 capturing self-perceived mental health were included as they complement each other. The MCS reflects broader dimensions of mental health, including psychological distress and functioning, whereas the EWB specifically assesses positive affective states and overall well-being. Including both measurements allows us to distinguish between general mental health and positive emotional states, which may show distinct associations with physical activity.

2.4. Characteristics of the study population

Participant age and sex were obtained via civil registration numbers. BMI was calculated from measured height and weight. Socio-demographic data, including education (short, medium and long), work status (employed, retired, unemployed), marital status (married, cohabiting, single/widowed), and smoking (non-smoker, former, current), were self-reported via questionnaire. Alcohol intake was assessed using Danish guidelines ($\leq$14 units/week for men, $\leq$7 for women) and classified as above or below the recommended limits.

Diabetes duration was calculated from diagnosis to baseline and expressed in years. Blood pressure was measured every 3 min for 30 min using an automated monitor. The mean of all readings was used. HbA1c was analysed from clinical samples taken near enrolment as part of the routine care at their general practitioner or hospital. Medication use was obtained during the clinical interview using the individual electronic medical record and was classified into four categories: 1) lipid-lowering drugs, 2) antihypertensive drugs, 3) glucose-lowering drugs, and 4) antidepressants and anxiolytics, with the last-mentioned retrieved from the Danish National Prescription Registry . The total burden and severity of comorbidities were calculated according to the Charlson Comorbidity Index, excluding diabetes and presented categorically: 1) 0, 2) 1–2 and 3) 3+ [35]. For further details please refer to the Electronic Supplementary Material (ESM) Characteristics of the study population.

2.5. Statistical analyses

Descriptive statistics were presented as medians with interquartile intervals (IQI) for continuous variables and as numbers with frequencies for categorical variables. The main analyses are based on the inclusion criteria and pre-specified according to our hypotheses: three bidirectional temporal associations between MVPA and three health outcomes (EWB, PCS and MCS using a three-wave, two-variable cross-lagged panel model (CLPM) in a structural equation model (SEM) (Fig. 1), adjusted for age and sex (Figs. 2-4). The decision to adjust solely for sex and age was informed by a directed acyclic graph mapping potential confounders and mediators to avoid bias from over-adjustment (ESM Fig. 4 and 5). In addition, as a sensitivity analysis, we evaluated the same associations in complete cases (defined above) (ESM Figs. 1-3). The three waves were baseline, 24 months, and 48 months of follow-up. We also tested for group differences between complete cases and participants who was not complete cases using Mann-Whitney Wilcoxon rank-sum test.

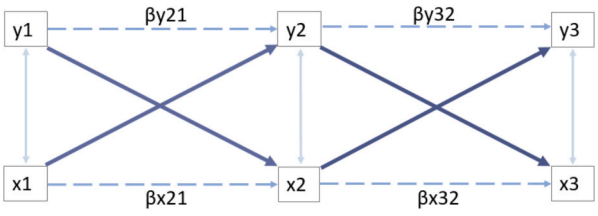

Fig. 1. Cross-lagged panel model Fig. 1. Illustration of the theoretical framework of a three-wave cross-lagged panel model. The blue stippled lines represent the stability path where coefficient βy21, for example, captures the stability of y1 on y2. The dark blue solid lines represent the cross-lagged effects. For example, λy21 represents the effect of y in wave 1 on x in wave 2. The opposite effect, λx21, represents the effect of x in wave 1 on y in wave 2.

The autoregressive parameters, in conceptual terms, describe the amount of stability in constructs over time. In this construct we operate with x and y to explain the autoregressive paths. Smaller (close to zero) autoregressive coefficients indicate more variance in the construct, meaning less stability or influence from the previous time point [36]. Larger autoregressive coefficients (close to one) indicate little variance over time, meaning more stability or influence from the previous time point [36]. These coefficients are also known as lag-1 effects or a Markov chain, as the model implies that only the prior wave information is important for the current status. We are effectively controlling for previous levels of x and y.

Cross-lagged parameters estimate the predictive influence of one variable on another across time points, thereby modelling potential directional or reciprocal effects [37]. These coefficients reveal whether variation in a predictor at time t forecasts changes in an outcome at time t + 1. When both cross-lagged paths are statistically significant and positive, the data support a reciprocal model of connection, wherein each construct influences the other over time. A single significant path suggests a unidirectional effect, while non-significant paths indicate no evidence of causal linkage [37]. For the interpretation of cross-lagged effect sizes, we follow the recommended benchmarks for a CLPM model, which is based on the 25th, 50th and 75th percentiles of the distribution, corresponding to a cross-lagged effect size of $\beta = 0.03$ indicating a small effect, $\beta = 0.07$ indicating a medium effect, and $\beta = 0.12$ indicating a large effect [38]. These recommended benchmarks are based on 25th, 50th and 75th percentiles, respectively, and should not be considered strict cut-offs. Accordingly, we interpret values near these benchmarks as small, medium or large cross-lagged effect sizes, acknowledging a gradual continuum between these values.

A cross-lagged panel model also controls for correlations within time points and autoregressive effects or stability across time. This model includes parameters, which include exogenous variance, correlations, cross-lagged paths, autoregressive paths, and endogenous residuals [36]. Estimates for cross-lagged effects now control for contemporaneous effects and variance across time. The causal relationships can be examined by comparing standardised coefficients of the cross-lagged paths. Cross-lagged effects capture the impact of one variable at a previous wave on another variable's current values [36]. All analyses were performed using the statistical software StataBE version 18.5. In the SEM model in Stata, we standardised the coefficients and the estimation method was maximum likelihood with missing values (MLMV) and we assume that missingness depends on observed variables, not unobserved and therefore is missing at random. We followed Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines.

3. Results

In this study, 972 participants were included according to the inclusion criteria mentioned above. At baseline, we had 644 participants with complete data, 565 at 24 months, and 437 at 48 months. We had 245 participants with complete data in all three measurement waves. The median age of the participants was 61.9 years (53.9–68.4) at baseline. The majority of the participants were males (59%), with stable sex distribution over time, and 57% reported a family history of type 2 diabetes mellitus. The median duration of diabetes mellitus at the time of baseline was 3.6 years (0.9–5.6). 74% of participants had no comorbidities, while 24% had one or two, and 3% had three or more. The participants presented with 89% taking at least one glucose-lowering drug, 74% taking lipid-lowering drugs, 73% taking

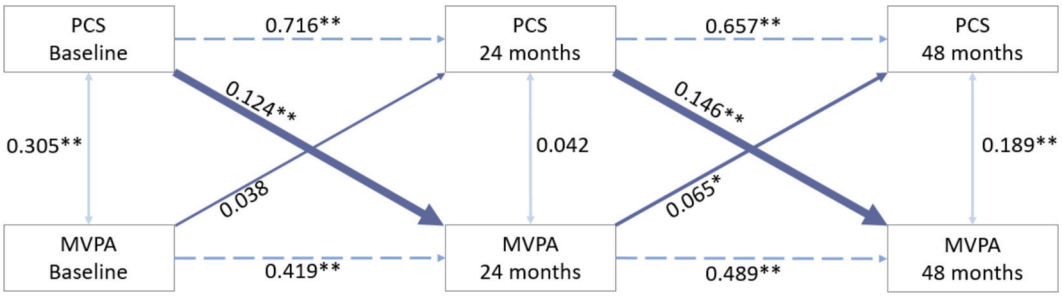

Fig. 2. Cross-lagged panel model for the association between the physical component summary score and moderate to vigorous physical activity Fig. 2. Cross-lagged panel model for the association between the physical component summary (PCS) score of the health-related quality of life questionnaire (SF-12) and moderate to vigorous physical activity (MVPA) assessed by accelerometry, all adjusted for age and sex. The blue dashed lines = autoregressive effects; the dark blue solid lines = cross-lagged effects; the grey/blue solid lines = cross-sectional associations at each measurement point. The dark blue solid lines depict cross-lagged effects, with line thickness scaled to represent the corresponding effect size. The associations are given as beta-coefficients; *p < 0.05, **p < 0.001.

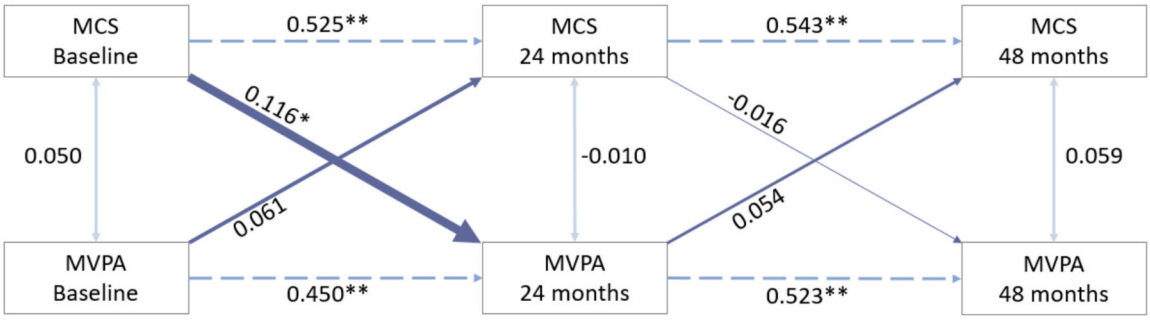

Fig. 3. Cross-lagged panel model for the association between the mental component summary score and moderate to vigorous physical activity Fig. 3. Cross-lagged panel model for the association between the mental component summary (MCS) score of the health-related quality of life questionnaire (SF-12) and moderate to vigorous physical activity (MVPA) assessed by accelerometry, all adjusted for age and sex. The blue dashed lines = autoregressive effects; the dark blue solid lines = cross-lagged effects; the grey/blue solid lines = cross-sectional associations at each measurement point. The dark blue solid lines depict cross-lagged effects, with line thickness scaled to represent the corresponding effect size. The associations are given as beta-coefficients; *p < 0.05, **p < 0.001.

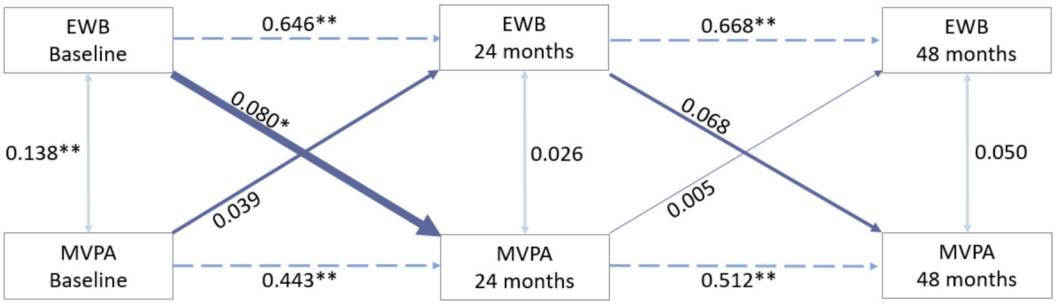

Fig. 4. Cross-lagged panel model for the association between the emotional well-being and moderate to vigorous physical activity Fig. 4. Cross-lagged panel model for the association between the emotional well-being (EWB) score based on the WHO-5 questionnaire and moderate to vigorous physical activity (MVPA) assessed by accelerometry, all adjusted for age and sex. The blue dashed lines = autoregressive effects; the dark blue solid lines = cross-lagged effects; the grey/blue solid lines = cross-sectional associations at each measurement point. The dark blue solid lines depict cross-lagged effects, with line thickness scaled to represent the corresponding effect size. The associations are given as beta-coefficients; *p < 0.05, and **p < 0.001.

antihypertensive drugs, and 28% taking antidepressants and anxiolytics. Full characteristics are presented in Table 1. Further information on characteristics for the 245 complete cases is available in ESM Table 1. In ESM Table 2 a comparison of complete cases (n = 245) and participants who was a part of the main analyses without being complete cases (n = 727) can be found.

3.1. Cross-lagged effects

The cross-lagged panel models revealed distinct patterns of directional effects (Figs. 2-4). The strongest finding was that PCS at baseline predicted MVPA at 24 months (β = 0.124, p < 0.001), likewise, PCS at 24 months predicted MVPA at 48 months (β = 0.146, p < 0.001), reflecting large cross-lagged effects of PCS on MVPA (Fig. 2; ESM Table 3). In contrast, MVPA at baseline did not predict PCS at 24 months (β = 0.038, p = 0.184). Nevertheless, MVPA at 24 months predicted PCS at 48 months (β = 0.065, p = 0.024), reflecting small to medium cross-lagged effects on PCS (Fig. 2; ESM Table 3). The complete case analysis (ESM Fig. 1; ESM Table 4,) supported these primary findings. PCS at baseline predicted MVPA at 24 months (β = 0.141, p = 0.018) and PCS at 24 months predicted MVPA at 48 months (β = 0.161, p = 0.003). Additionally, MVPA at baseline did significantly predict PCS at 24 months (β = 0.114, p = 0.019), though not at 48 months (β = 0.089, p = 0.090), reinforcing the stronger predictive role of PCS over MVPA.

Table 1
Baseline characteristics according to inclusion criteria (n = 972).

Characteristics	
Age (years)	61.9 (53.9–68.4)
Sex (n, %)	
Female	398 (41.0)
Diabetes mellitus duration (years)	3.6 (0.9–5.6)
Body Mass Index (kg/m^2)	31.0 (27.7–34.9)
Family history of T2D (n, %)	
Yes	558 (57.4)
Health-related quality of life[a]	
SF-12 Physical Component Summary score	50.4 (40.9–54.8)
SF-12 Mental Component Summary score	55.3 (46.6–58.8)
Emotional well-being	
WHO-5 score	72 (52–80)
Physical activity Intensities (min/day)[a]	
Moderate	10.0 (4.3–18.6)
Vigorous	0.6 (0.2–1.6)
MVPA	11.0 (4.8–20.5)
Steps (per/day)	3863.5 (2484.5)
Smoking status (%)	
Non-smoker	404 (41.6)
Former	390 (40.1)
Current	178 (18.3)
Alcohol consumption above recommendations (n, %)	182 (18.7)
Marital status (n, %)	
Married or living with a partner	741 (76.2)
Education level (n, %)	
Short term	409 (42.3)
Medium term	502 (51.9)
Long term	56 (5.8)
Work status (n, %)	
Employment including part-time employment	432 (44.4)
HbA1c (mmol/mol)	49 (45–55)
Baseline Charlson Comorbidity Index	
0	712 (73.6)
1–2	228 (23.6)
3+	28 (2.8)
Medication (n, %)	
Glucose-lowering drugs	863 (88.8)
Lipid-lowering drugs	714 (73.5)
Anti-hypertensive drugs	711 (73.2)
Antidepressants and anxiolytics	270 (27.8)

[a] Variable contains missing data. Continuous data is presented as median with interquartile intervals (IQI). Categorical data is presented as numbers with frequencies (%).

MCS at baseline predicted MVPA at 24 months (β = 0.116, p = 0.001), reflecting a large cross-lagged effect on MVPA (Fig. 3; ESM Table 5). However, MCS at 24 months did not predict MVPA at 48 months (β = -0.016, p = 0.653). MVPA at baseline did not predict MCS at 24 months (β = 0.061, p = 0.065), and MVPA at 24 months did not predict MCS at 48 months (β = 0.054, p = 0.090). Thus, their cross-lagged effects were interpreted as small to medium (Fig. 3; ESM Table 5). The complete case analysis (ESM Fig. 2; ESM Table 6) aligned with the main analysis: MCS at baseline predicted MVPA at 24 months (β = 0.136, p = 0.021) while MCS at 24 months showed no effect on MVPA at 48 months (β = -0.015, p = 0.785). MVPA did not predict later MCS in either time interval, confirming the time-sensitive and unidirectional nature of this relationship.

EWB at baseline predicted MVPA at 24 months by demonstrating a medium to large cross-lagged effect (β = 0.080, p = 0.023), while EWB at 24 months showed a small to medium cross-lagged effect on MVPA at 48 months without being significant (β = 0.068, p = 0.058) (Fig. 4; ESM Table 7). Conversely, MVPA did not significantly predict later EWB at any interval but showed a small to medium cross-lagged effect on EWB at 24 months (β = 0.039, p = 0.171) and no effect on EWB at 48 months (β = 0.005, p = 0.858) (Fig. 4; ESM Table 7). The complete case analysis (ESM Fig. 3; ESM Table 8) did not fully replicate these findings. While EWB at baseline did not predict MVPA at 24 months (β = 0.114, p = 0.057), EWB at 24 months had a medium to large cross-lagged effect on MVPA at 48 months but was non-significant (β = 0.089, p = 0.114). MVPA showed a small to medium cross-lagged effect on EWB at 24 months without being significant (β = 0.063, p = 0.167). However, MVPA did not show an effect on EWB at 48 months (β = -0.006, p = 0.900), reinforcing the limited longitudinal influence of MVPA on EWB.

3.2. Autoregressive effects

Across all constructs – PCS, MCS, EWB, and MVPA – autoregressive paths indicated high stability over the 48 months, as seen in both main and complete case models (Figs. 2-4; ESM Figs. 1-3).

PCS at baseline strongly predicted PCS at 24 months, which in turn predicted PCS at 48 months (ESM Table 3). Comparable stability was observed for MCS (ESM Table 5) and EWB (ESM Table 7), with strong autoregressive coefficients (>0.6) in all intervals. MVPA also exhibited consistent temporal stability (ESM Tables 3, 5, 7). All findings in the main analyses were corroborated in the complete case analyses (ESM Tables 4, 6, 8).

3.3. Cross-sectional associations

At each wave, we investigated the cross-sectional associations between the three health-related components, PCS and MCS in HRQoL, EWB and MVPA within the SEM framework of the cross-lagged panel model. The associations were also adjusted for age and sex. Here, we found a positive association between the PCS and MVPA at baseline (β = 0.305, p < 0.001) and at 48 months (β = 0.189, p < 0.001), but not at 24 months (ESM Table 3. In the associations between MCS and MVPA, no significant associations were found (ESM Table 5). In the associations between EWB and MVPA, a positive association was observed only at baseline (β = 0.138, p < 0.001) (ESM Table 7).

4. Discussion

This longitudinal study determined whether bidirectional associations were present between HRQoL, EWB and MVPA over 48 months in individuals recently diagnosed with type 2 diabetes mellitus. Across all models, we observed high temporal stability in PCS, MCS, EWB, and MVPA, indicating that baseline measures strongly predict future measures. When examining the cross-lagged effects, PCS emerged as the most consistent predictor of subsequent MVPA, underscoring the pivotal role of physical functioning in sustaining physical activity during early-stage type 2 diabetes mellitus. Although MCS and EWB also predicted MVPA at 24 months, these associations were attenuated at 48 months. In contrast, MVPA had generally weaker and less consistent predictive effects on later PCS, MCS, or EWB, pointing to a predominantly unidirectional relationship where physical and mental health more reliably predict future physical activity levels than vice versa.

The association between PCS and MVPA was consistent across both the 0–24 and 24–48 month intervals, highlighting the importance of self-perceived physical functioning in supporting sustained physical activity among individuals newly diagnosed with type 2 diabetes mellitus. The PCS, which reflects an individual's perceived capacity to perform daily physical tasks, has been widely acknowledged as a determinant of exercise participation [39], with higher scores associated with fewer perceived physical barriers such as fatigue, pain, or mobility limitations [1,2]. This relationship is of particular relevance to individuals living with type 2 diabetes mellitus, in which preserved functional independence is critical for long-term behavioural adherence and effective disease management [3,14].

Although the predictive effects of MVPA on subsequent PCS were statistically significant only for the 24–48 month interval, the direction of estimates remained consistent across time points. This was further supported by the complete case analysis, which demonstrated statistically significant associations. These cross-lagged effects suggest that short-term increases in MVPA may not be sufficient to produce noticeable improvements in self-perceived physical functioning, consistent

with prior findings indicating that enhancements in physical quality of life often require sustained or higher-intensity interventions [4,11]. Moreover, the multifactorial nature of PCS encompassing pain, fatigue, and EWB may require a more structured and sustained physical activity engagement to elicit change, especially among individuals coping with the complex demands of diabetes mellitus and related comorbidities [22].

Our study extends prior research by confirming these associations in a large cohort of individuals recently diagnosed with type 2 diabetes mellitus. Previous studies have often focused on mixed populations (prediabetes mellitus, type 1 diabetes mellitus and type 2 diabetes mellitus or chronic-phase diabetes mellitus) in cross-sectional settings [1,5].

In individuals with diabetes, some studies have revealed a positive association between physical activity and HRQoL [41–45], where some have found HRQoL to decrease with decreasing levels of physical activity [4,46]. Objective accelerometry data, rather than self-reported, strengthened our estimates by reducing recall bias and social-desirability bias. For example, a Canadian cohort study found that individuals with type 2 diabetes mellitus meeting the physical activity recommendations were more likely to report higher PCS than MCS [47], which reinforces the notion that PCS of HRQoL is more tightly coupled to physical activity levels than the MCS of HRQoL [47]. Consistent with evidence, our longitudinal data reinforce this differential association and demonstrate its persistence over time.

The findings of this study suggest a limited, inconsistent, and time-sensitive relationship between mental health, as measured by the MCS and EWB scores, and subsequent MVPA among individuals recently diagnosed with type 2 diabetes mellitus. Although MCS significantly predicted MVPA at the 24-month time point, this effect was not maintained at 48 months. Conversely, EWB demonstrated only a small and statistically non-significant influence on MVPA across all time points. The present findings suggest that mental health may play a role in initiating physical activity in the early phase following diagnosis, but its impact on long-term behaviour maintenance appears to be attenuated over time. This contrasts with dominant psychological models, which suggest that better mental health contributes to increased physical activity through mechanisms such as elevated mood, motivation, and energy levels [48]. However, our results align with previous research conducted in chronic ill populations where physical symptoms such as pain, fatigue, and mobility limitations often override psychological influences on physical activity [49]. In individuals with type 2 diabetes mellitus, these physical constraints may overshadow psychological facilitators of physical activity, particularly as the disease progresses.

Clinical guidelines emphasise the importance of physical activity for people with type 2 diabetes mellitus [14,17,18]. However, it remains challenging for many individuals to maintain lifestyle changes over time [46]. The deterioration of MCS's predictive value over time may be indicative of psychological adaptation, ceiling effects, or even intervention fatigue [4,48]. Importantly, MVPA did not significantly predict future MCS or EWB in our study, challenging the assumed bidirectional model. While some studies report psychological benefits of MVPA [40,47], *meta*-analyses have shown these effects are context-dependent and highly dependent on factors such as baseline mental health status, exercise intensity, and the intervention design [4,15,48].

Structured, supervised exercise programmes appear most effective in delivering psychological benefits. For example, the Italian Diabetes mellitus and Exercise Study, a randomised controlled trial, demonstrated that supervised exercise training significantly improved mental HRQoL [45], and a network *meta*-analysis of randomised controlled trials found that combined aerobic and resistance exercise modalities produced favourable effects on both physical and psychological health outcomes [15]. By contrast, observational studies suggest that increases in free-living physical activity, in the absence of behavioural or emotional support, may offer limited psychological well-being benefits [40,43]. These findings suggest that psychological gains from MVPA in type 2 diabetes mellitus are not guaranteed but rather depend on how and under what circumstances the physical activity is implemented.

The present study has several strengths. Its three-wave longitudinal design (baseline, 24 months, and 48 months) enabled an in-depth exploration of the bidirectional associations between MVPA, PCS, MCS, and EWB, using SEM to disentangle autoregressive and cross-lagged effects. This approach controls for prior levels of both exposure and outcome, ensuring observed effects reflect true temporal associations rather than baseline differences [37]. A further strength is the use of a unique cohort comprising individuals with recently diagnosed type 2 diabetes mellitus, recruited from primary care. This sample is representative of the national DD2 cohort, enhancing generalisability to Danish individuals who were recently diagnosed with type 2 diabetes mellitus [26]. The use of validated instruments (SF-12 and WHO-5), in conjunction with objective accelerometer-based activity data (Axivity AX3), further strengthens the study's methodological rigour.

Limitations of this study include participant attrition over the 48-month follow-up period, which may have introduced selection bias and reduced generalisability, particularly to individuals with lower adherence or poorer health profiles. Although accelerometers provide objective estimates of physical activity, they may underestimate MVPA, as they often fail to capture activities such as strength training or household tasks that contribute to energy expenditure. Another limitation concerns the reliance on self-reported HRQoL and EWB data, which may introduce reporting bias and compromise the accuracy of the observed associations over time. Furthermore, our 24 and 48-months follow-ups were for a proportion during the Covid-19 pandemic in Denmark (18th of March 2020 to 10th of September 2021), which could have influenced our measures of physical activity and psychological well-being. While SEM-based cross-lagged panel models offer valuable insights into temporal associations, they do not establish causality with absolute certainty. Traditionally CLPM conflates stable between-person differences with within-person change, which could influence the interpretation of cross-lagged effects. If more measurement waves had been available, we would have considered using a RI-CLPM model [37]. Regarding missing data, we assume that data were missing at random and applied the maximum likelihood estimation to mitigate bias. Although the number of complete cases was limited, supplementary analyses confirmed that results from complete case models were consistent with the main findings, suggesting robustness to data loss. Finally, while our statistical models were adjusted only for age and sex, this was a cautious choice to maintain model thriftiness and avoid overfitting, given the sample size and complexity of the structural models. We acknowledge that other clinical variables, e.g. comorbidities, BMI, or type 2 diabetes mellitus duration may act as potential confounders. However, we did not include those factors due to model complexity and risk of over-adjustment. Future studies with larger samples may explore the impact of broader covariate adjustment on the observed associations.

5. Conclusion

Our findings show that more favourable PCS is a consistent predictor of higher future MVPA among individuals recently diagnosed with type 2 diabetes mellitus. In contrast, the expected reciprocal effects were weaker and inconsistent, with no significant predictive effects observed from MVPA to MCS or EWB at any time point. These findings suggest that interventions to promote MVPA should prioritise strategies that maintain or improve physical functioning early in the disease trajectory, thereby enhancing both actual capacity and patients' confidence in their abilities. While psychological factors such as EWB and mental health may help initiate physical activity shortly after diagnosis, their influence appears to diminish over time. Clinicians should consider early screening and targeted interventions for low HRQoL, with particular attention to physical functioning, to foster sustainable physical activity patterns and optimise long-term disease management outcomes.

CRediT authorship contribution statement

Sofie Frigaard Kristoffersen: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis. **Sidsel Louise Domazet:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Frans Pouwer:** Writing – review & editing. **Jens Steen Nielsen:** Writing – review & editing. **Thomas Bastholm Olesen:** Writing – review & editing, Resources. **Jacob Volmer Stidsen:** Writing – review & editing, Resources, Funding acquisition, Data curation. **Michael Hecht Olsen:** Writing – review & editing. **Kurt Højlund:** Writing – review & editing, Validation, Supervision, Funding acquisition.

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Declaration of competing interest

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

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Data availability statement.

The datasets presented in this article are not readily available because they contain data that is owned by The Danish Health Data Authority, which cannot be made publicly available or shared by third parties due to Danish data protection legislation. Own data can be made available upon reasonable request. Requests to access the datasets should be directed to Jacob Volmer Stidsen, jacob.volmer.stidsen@rsyd.dk.

Contribution statement

JVS did the conception of the IDA study and the acquisition of data. SLD conceptualised the study. SFK performed data management, conducted statistical analysis and drafted the initial manuscript. FP provided expertise on psychological aspects. SLD, JSN, JVS, TBO, MHO, and KH contributed with expert knowledge on type 2 diabetes mellitus. All authors contributed to the interpretation of data and the drafting of the manuscript, as well as critically revising the manuscript draft. All authors approved the final version of the manuscript to be published. KH is the guarantor of this work and, as such, had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.diabres.2026.113185.

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