Diabetes, Metabolic Syndrome and Obesity

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ORIGINAL RESEARCH

Formation Mechanisms, Interrelationships, and Effects of Cognitive Factors on Diet and Physical Activity During the Post-Bariatric Surgery Period: A Cross-Sectional Study Based on Compensatory Carry-Over Action Model

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Background: Diet and physical activity (PA) are pivotal behaviors for managing energy balance post-bariatric surgery. Given the need for dual behavioral management, understanding the interplay of cognitive factors influencing these behaviors is crucial. This study applied the compensatory carry-over action model (CCAM) to explore the impact of cognitive factors on behaviors and their subsequent effects on subjective health outcomes.

Methods: This cross-sectional study was conducted among patients at the third month after bariatric surgery in China. Data on diet and PA status, behavioral cognitive factors (intention, self-efficacy, compensatory belief, transfer cognition), and subjective health outcomes (perceived stress, well-being, quality of life) were collected. Structural equation model (SEM) was employed to test hypotheses in CCAM and assess mediation relationships.

Results: Analysis of data from 239 patients revealed the following: (1) Among antecedent cognitive factors, only compensatory belief significantly influenced diet ($P<0.001$). (2) Intention and self-efficacy directly correlated with their respective behaviors, while compensatory belief affected intention, and transfer cognition impacted self-efficacy ($P<0.05$), aligning with CCAM hypotheses. (3) PA demonstrated significant influence only on perceived stress ($P=0.004$), whereas diet significantly affected all subjective health outcomes ($P<0.05$). (4) Mediation analysis indicated intention partially mediated the relationship between compensatory belief and diet and fully mediated the relationship between compensatory belief and PA. Self-efficacy completely mediated the relationship between transfer cognition and diet and PA.

Conclusion: Transfer cognition's carry-over effect did not directly influence behaviors among antecedent cognitions. Interventions should primarily target improving diet by mitigating compensatory belief. Moreover, diet exhibited a more pronounced impact on overall health compared to PA. Consequently, prioritizing dietary intervention over PA intervention is warranted based on the analysis of CCAM and the aim of promoting joint behaviors post-bariatric surgery.

Keywords: bariatric surgery, compensatory carry-over action model, diet, physical activity, cognitive factors

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Introduction

Obesity, defined as excessive fat accumulation in the body, is regarded as an epidemic in the 21st century. According to the latest epidemiological report published by the World Health Organization, more than 39% of adults globally are overweight (body mass index [BMI] ≥25 kg/m^2), and 13% of them are obese (BMI ≥30 kg/m2).[1] Obesity is a significant public health issue, contributing to various metabolic diseases and imposing substantial social and economic burdens.[2] Recently, bariatric surgery has been considered the most effective treatment approach for obesity.[3] The excess weight loss rate (EWL%) at 10 years after surgery can reach 60%~70%, the remission rate of type 2 diabetes at 1 year after surgery is 80%,[4] and the average incident rate of hepatic steatosis has reduced from 37.4% to 16.0%.[5] After bariatric surgery, patients are advised to maintain good lifestyle habits to prevent weight gain. Guidelines recommend a diet high in protein, low in carbohydrates and saturated fats, with daily supplementation of vitamins, iron, and trace elements.[6] Physical activity (PA), defined as any bodily movement produced by the skeletal muscles that requires energy expenditure, is recommended for postoperative patients to achieve 150 minutes or more of moderate-intensity aerobic activity per week. However, during the post-bariatric period, only 11% of patients carry out adequate PA 1 year after surgery,[7] 26% of patients fail to follow dietary recommendations, 73% of patients often eat high-fat foods,[8] and 29% of patients reduce their PA by 50% compared to pre-surgery levels. These lifestyle habits will lead to unsatisfactory weight outcomes after surgery in the long term.[9]

Diet and PA directly influence energy intake and expenditure, and are subject to cognitive factors, environmental factors, interpersonal relationships, and socio-cultural contexts.[10] Among these, cognitive factors are central in many behavior change theories, impacting behavior selection, execution, and maintenance, and are easier to intervene and adjust.[11] Bergh et al[12] suggested that cognitive factors such as self-efficacy, intention, and behavioral planning in patients undergoing bariatric surgery are related to the patients' postoperative dietary compliance. Sarwer et al[13] reported that self-efficacy, perceived benefits and barriers are the main cognitions that affect post-bariatric patients' ability to perform PA. Dietary and PA management during the post-bariatric surgery period is often carried out simultaneously. Moreover, interrelationships exist between the two behaviors (diet and PA), which is mediated by cognitive factors. Geers et al[14] demonstrated that PA and consumption of fruits and vegetables by obese individuals were significantly mediated by cognitive beliefs and subjective norms. As for compensatory belief (CB), obese people may use CB to relieve the guilt caused by executing an unhealthy behavior through the execution of another compensatory healthy behavior, thereby leading to poor overall health.[15]

Accumulating evidence in published literature suggests that post-bariatric patients may need dual behavioral management for diet and PA, and these behaviors are jointly affected by various cognitions. To explore the formation mechanism of such behaviors from perspective of cognitive factors, we chose to use the compensatory carry-over action model (CCAM) in the present study to provide a theoretical basis for this study.

Theoretical Framework and Research Hypotheses

CCAM was proposed by Professor Lippke[16] in 2014 to provide better guidance for prevention and management of diabetes and obesity (Figure 1). Based on the health action process approach (HAPA) theory, CCAM combines specific cognitive factors to link multiple single behaviors together. CCAM's primary constructs encompass intention, self-efficacy, CB, and transfer cognition (TC). CCAM assumes that CBs and TCs serve as principal antecedents for the association among diverse health behaviors, thus categorizing them as "antecedent cognitive factors". CB is defined as "a belief that the negative effects of participating in unhealthy behaviors can be mitigated by the positive effects of another healthy behavior".[17] TC denotes factors embodying the carry-over mechanism of individual volition, wherein one healthy behavior facilitates the adoption of another wellness behavior.[18] Experience, skills, knowledge, and self-efficacy typically constitute elements of this mechanism, intertwining diverse behaviors at the belief level. Each behavior's development is directly driven by intention and self-efficacy. CB modulates the level of behavior intention, while TC modulates the level of self-efficacy. The adoption of healthy behaviors can enhance various subjective health outcomes.

CCAM has been demonstrated by various behavioral science studies to effectively elucidate the intricate relationship between diverse health behaviors and their determinants. A retrospective cohort study revealed that changes in self-efficacy for PA predicted changes in self-efficacy for fruit/vegetable intake, and vice versa, this phenomenon was defined as "coaction" originating from CCAM.[19] Tan et al explored the relationship among restful sleep, PA, and intake of

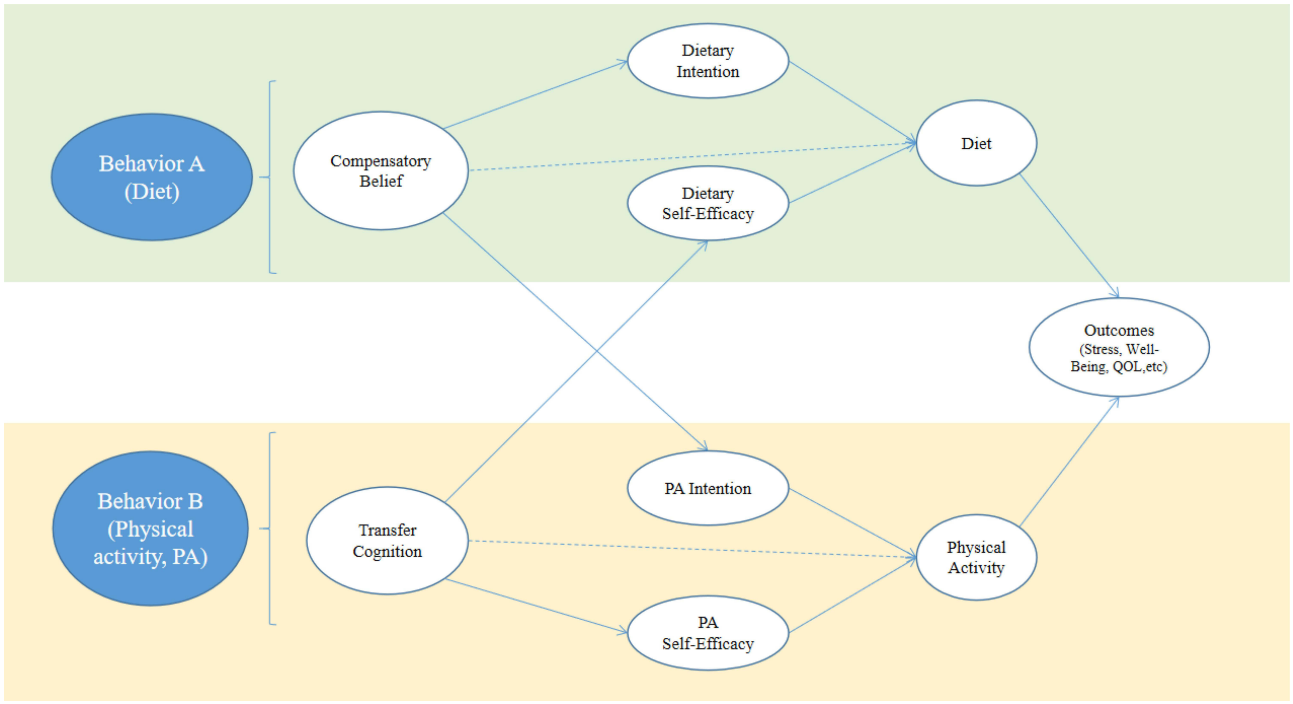

Figure 1 Framework of compensatory carry-over action model. The solid lines refer to the relation hypothesis in the original compensatory carry-over action model (CCAM); The dotted lines refer to supplementary hypothesis in this study.
Abbreviations: PA: physical activity; QOL: quality of life. In this study, we set behavior A as diet, and behavior B as PA.

vegetables by applying CCAM, and identified interactive relationships among these behaviors through path analysis.[20] In CCAM, CB and TC influence behavior development through intention and self-efficacy as mediating factors. However, direct relationships may also exist between both CB, TC and behaviors. Geers et al demonstrated that obese individuals shared subjective norms in fruit/vegetable intake and PA, which directly reflects the presence of the TC mechanism.[14] In studies on alcohol consumption and smoking, CBs in these domains significantly detrimentally influenced healthy behaviors.[21,22] Moreover, CCAM primarily emphasizes subjective outcomes like perceived stress and happiness as health outcomes, given that cognitive factors are central to the model. Therefore, greater emphasis should be placed on individuals' subjective experiences.[16] In fact, several studies have widely demonstrated the effects of diet and PA on physiological indicators such as BMI and EWL%.[23,24] Therefore, this study placed greater emphasis on subjective outcomes. We also focused on patients' quality of life (QOL) as QOL is a crucial assessment parameter in Bariatric Analysis and Reporting Outcome System (BAROS).[25] In summary, based on CCAM and comprehensive literature review, the present study proposed several hypotheses. Table 1 lists the original hypothetical paths.

Considering the aforementioned information, the present study applied CCAM to investigate the effects of cognitive factors, namely "intention, self-efficacy, CB, and TC", on patients' diet and PA during the post-bariatric surgery period, and to determine the effects of behaviors on subjective health outcomes. We developed a structural equation model (SEM) to elucidate the formation mechanisms and interrelationships between diet and PA.

Methods

Study Participants

This cross-sectional study was conducted in the Bariatric Surgery Center of the First Affiliated Hospital of Nanjing Medical University. According to the formula for calculating the sample size of cross-sectional studies $n = \left(\sigma \frac{z_{1-\alpha/2}+z_{1-\beta}}{\mu-\mu_0}\right)^2$, we set $\alpha = 0.05$, $\beta = 0.8$, and considering that diet behavior (the Dietary Adherence Scale after Bariatric Surgery scale) to be the core variable in this study, in bariatric population the $\sigma = 10.08$, $\mu = 54.90$,[26] and the difference of μ_0 in this study was expected to be 2.00, also considering a 10% dropout rate, the calculated sample size

Table 1 Original Hypothetical Paths Based on CCAM

Category of Hypothesis	Item
Hypothesis 1 (H1): Influence of cognitive factors on behavior	H1a: Compensatory belief has a negative impact on diet H1b: Dietary intention has a positive impact on diet H1c: Dietary self-efficacy has a positive impact on diet H1d: Transfer cognition has a positive impact on diet H1e: Compensatory belief has a negative impact on PA H1f: PA intention has a positive impact on PA H1g: PA self-efficacy has a positive impact on PA H1h: Transfer cognition has a positive impact on PA
Hypothesis 2 (H2): Influence of antecedent cognition on mediated cognition	H2a: Compensatory belief has a negative impact on dietary intention H2b: Compensatory belief has a negative impact on PA intention H2c: Transfer cognition has a positive impact on dietary self-efficacy H2d: Transfer cognition has a positive impact on PA self-efficacy
Hypothesis 3 (H3): Influence of behavior on subjective health outcomes	H3a: Positive dietary behavior reduces stress H3b: Positive dietary behavior increases well-being H3c: Positive dietary behavior increases physical QOL H3d: Positive dietary behavior increases mental QOL H3e: Positive PA behavior reduces stress H3f: Positive PA behavior increases well-being H3g: Positive PA behavior increases physical QOL H3h: Positive PA behavior increases mental QOL
Hypothesis 4 (H4): Indirect influence of antecedent cognition on behavior	H4a: Through dietary intention, compensatory belief has an indirect negative impact on diet H4b: Through PA intention, compensatory belief has an indirect negative impact on PA H4c: Through dietary self-efficacy, transfer cognition has an indirect positive impact on diet H4d: Through PA self-efficacy, transfer cognition has an indirect positive impact on PA

Notes: H1a refers to hypothesis 1a; the other hypotheses were designated in the same way.
Abbreviations: CCAM: compensatory carry-over action model; PA: physical activity; QOL: quality of life.

was at least 219 cases. A convenient sampling method was used to select the study subjects. Patient recruitment was conducted through the attending physician of our department during the postoperative follow-up. We opted to gather patient data at 3-month post-surgery, aligning with guidelines recommending the resumption of normal diet and initiation of structured resistance training during this period. This time point is critical for physiological recovery and the cultivation of healthy behavior patterns.

Overall, 281 patients who attended a follow-up visit in our surgery center at the third month after bariatric surgery *(have returned to a normal diet)* between August 2021 and August 2022 were selected, and relevant patient data were collected. The inclusion criteria were as follows: (1) patient age between 18 and 60 years old; (2) bariatric surgery being performed for the first time; (3) ability to understand the communicating language; and (4) volunteering to participate in this study. The exclusion criteria were as follows: (1) presence of severe postoperative complications (gastrointestinal bleeding, anastomotic leakage, intestinal obstruction); (2) presence of serious primary diseases (diseases of the cardio-cerebrovascular system, lungs, kidneys, etc.); (3) limited mobility due to disability; and (4) inability to eat properly due to oral problems.

Measures

Subjects completed the questionnaire under the guidance of the researcher, and data of general patient characteristics, status of diet and PA, status of behavioral cognitive factors, and status of subjective health outcomes were collected.

General Characteristics

Information of sex, age, working status, education level, operation method, preoperative BMI, current BMI, comorbidities, and complications was collected.

Status of Diet and PA

The Dietary Adherence Scale after Bariatric Surgery,[26] designed by Zhu, contains 16 items, assessing 4 dimensions of diet control, nutrient intake, fluid intake, and eating habits. It uses a 5-point Likert scale, wherein the total score is 16–80 points. The higher the score, the better the dietary compliance. The Cronbach's α value was 0.825.

International Physical Activity Questionnaire-Short Form,[27] developed by the International Physical Activity Measurement Working Group, consists of 7 items that evaluate the frequency and duration of high-intensity PA, moderate-intensity PA, walking, and sedentary behaviors of individuals. It uses metabolic equivalent (MET) assignment according to the intensity of the activity to calculate the amount of PA of individuals within 1 week. To facilitate data analysis using SEM, this study used the amount of PA (MET -min/w) to reflect the status of PA.

Status of Behavioral Cognitive Factors

Attitude-Social influence-Efficacy Questionnaire after Bariatric Surgery, developed by Zhu,[26] consists of 28 items, assessing 4 dimensions of intention, attitude, social influence, and self-efficacy. It uses the 5-point Likert scale. This study used the intention (4 items, total score 4–20 points) and self-efficacy (7 items, total score 7–35 points) subscale. The higher the score, the higher the dietary intention and the higher the self-efficacy. The Cronbach's α value was 0.930. Considering potential dietary habit differences between Eastern and Western populations, we selected bariatric surgery patients' dietary behavior and cognitive factors assessment tools developed by Chinese researchers.

Physical Activity Intention Scale, designed by Lippke,[28] consists of 5 items. It uses the 4-point Likert scale, and the total score ranges from 5 to 20 points. The higher the score, the stronger the willingness of the individual to engage in PA. The Cronbach's αvalue was 0.785.

Self-Efficacy for Exercise scale, developed by Lee,[29] consists of 9 items, and each item is scored from 0 (no confidence) to 10 (very confident), with the total score ranging from 0 to 90. The higher the score, the stronger the confidence gained by the individual in adhering to PA despite facing difficulties. The Cronbach's α value was 0.878.

Compensatory health Beliefs Scale, developed by Knauper,[17] is a 17-item scale that assesses the extent to which individuals believe that the negative effects of unhealthy behaviors can be compensated by engaging in healthy behaviors. In the present study, we used a simplified version of this scale, designed by Fleig,[18] consisting of 4 items that are specific to diet and PA. It uses a 5-point Likert scale, with the total score ranging from 4 to 20 points. The higher the scores, the stronger the CBs the individual had. The Cronbach's α value was 0.880.

Transfer Cognition Scale, developed by Fleig,[18] consists of 6 items that evaluate an individual's tendency to apply knowledge or abilities acquired in one behavior in another behavior. It uses the 5-point Likert scale, with the total score ranging from 6 to 30 points. The higher the scores, the stronger the TC. The Cronbach's α value was 0.650.

Status of Subjective Health Outcomes

Perceived Stress Scale, developed by Cohen,[30] consists of 14 items that assess 2 dimensions of loss of control and tension. It uses the 5-point Likert scale, with the total score ranging from 14 to 70 points. The higher the scores, the greater the stress. The Cronbach's α value was 0.750.

General Well-Being schedule, developed by Campbell,[31] consists of 18 items that assess 6 dimensions of well-being, self-control, vitality, depression, anxiety, and general health. It uses a 6-point response scale for the first 14 questions and a 10-point rating scale for the remaining 4 questions. The higher the score, the stronger the sense of well-being. The Cronbach's α value was 0.850.

The 12-item Short Form Health Survey, developed by the Boston Institute of Health Education (USA),[32] consists of 12 items that evaluate the effects on health, which is a measure of health-related QOL of individuals. It assesses 8 domains of physical functioning, role-physical, bodily pain, general health, vitality, social functioning, role-emotional, and mental health. After calculating in different ways, the physical component summary (PCS) and mental component

summary (MCS) can be measured. The higher the scores, the better the health-related QOL. The Cronbach's α values for PCS and MCS were 0.856 and 0.864, respectively.

Statistical Analyses

We used IBM SPSS Statistics 26.0 and AMOS 24.0 (Armonk, NY, USA) to perform statistical analyses of the collected data. We first performed linear regression analysis to analyze whether or not the influencing relationships in the original hypothetical paths were valid and then established an SEM based on the preliminarily verified model for path analysis. We finally tested the mediation relationships between cognitive factors and behaviors. Root mean square error of approximation, goodness-of-fit indices, comparative fit index, and χ^2/df were calculated to evaluate the fitness of the model. A 2-sided p value of <0.05 was considered to indicate a statistically significant difference.

Results

General Information of the Study Participants

In this study, a total of 281 questionnaires were distributed, of which 239 (85.05%) were valid, 42 questionnaires were excluded because the response of regularity or unanswered items exceeded 20%. Among the 239 participants, 69.5% were female (n=166), and the average age was 30.92±7.41 years. The average preoperative BMI was 38.17±7.26 kg/m^2, and the average BMI at the third postoperative month was 28.48±5.37 kg/m^2. Table 2 presents data of the general information of the study participants. Table 3 presents data of the cognitive, behavioral, and subjective outcome status of the study participants.

Table 2 Demographic and Clinical Information of the Study Participants

Variables	Classification	Quantity	Percentage (%)
Gender	Male	73	30.5
	Female	166	69.5
Age, years	<30	113	47.3
	30–40	103	43.1
	>40	23	9.6
Working status	Employed	192	80.3
	Retired, unemployed or at school	47	19.7
Education level	Primary school or below	4	1.7
	Middle school	19	7.9
	High school or technical school	34	14.2
	College, undergraduate or above	182	76.2
Operation	Sleeve gastrectomy	148	61.9
	Roux-en-Y gastric bypass	9	3.8
	SG plus jejunojejunal bypass	66	27.6
	SG plus duodenojejunal bypass	16	6.7
Preoperative BMI, kg/m^2	<27.5	2	0.8
	27.5–32.5	41	17.2
	>32.5	196	82.0
Current BMI, kg/m^2	<27.5	114	47.7
(3 months after surgery)	27.5–32.5	87	36.4
	>32.5	38	15.9
Comorbidities (hypertension, T2DM, OSA, NAFLD, etc.)	Yes	129	54.0
	No	110	46.0
Complications (bleeding, leakage, acid reflux, etc.)	Yes	11	4.6
	No	228	95.4

Abbreviations: BMI, body mass index; NAFLD, nonalcoholic fatty liver disease; OSA, obstructive sleep apnea; SG, sleeve gastrectomy; T2DM, type 2 diabetes mellitus.

Table 3 Status of Participants' Cognitive, Behavioral, and Subjective Health Outcome

Variables		Min	Max	Score
Status of behavioral cognitive factors	Dietary intention	8	20	16.61±2.57
	Dietary self-efficacy	11	35	25.61±5.94
	PA intention	5	25	16.99±4.20
	PA self-efficacy	9	99	55.90±23.05
	Compensatory belief	4	20	8.64±4.41
	Transfer cognition	6	30	23.03±6.47
Status of behaviors	Diet	29	80	58.76±8.94
	PA (MET-min/w)	0	18,372	2079 (693, 4428)
Status of subjective health outcomes	Perceived stress	3	46	23.33±7.17
	Well-being	40	110	80.33±13.14
	Physical quality of life	25.91	63.34	48.12±8.09
	Mental quality of life	14.24	67.41	46.98±8.86

Notes: MET-min/w: the amount of activity per week calculated according to metabolic equivalents; PA: physical activity. The data for PA had a skewed distribution and are therefore presented as median and interquartile range. Data of the other variables are presented as mean±standard deviation.

Preliminary Inspection of the Path Relationships in the Original Hypothetical Model

According to the results of linear regression analysis, the influences of TC on diet (H1d, p=0.131), CB on PA (H1e, p=0.522), TC on PA (H1h, p=0.071), PA on well-being (H3f, p=0.104), and PA on physical aspects of QOL (H3g, p=0.354) did not show any statitically significance. Therefore, we eliminated these paths in the subsequent SEM fitting. Paths in the other hypotheses were initially verified to be significant (p<0.05). Table 4 presents the standardized coefficients and the corresponding hypotheses. Figure 2 shows the adjusted hypothetical paths in the preliminarily verified model.

Table 4 Results of Linear Regression Analysis Based on CCAM

Dependent Variable	Independent Variable	Standardized β	|t|	*P*	Hypothesis	Established
Diet	CB	−0.228	2.981	0.003*	H1a	Yes
	Dietary In	0.335	5.604	<0.001*	H1b	Yes
	Dietary SE	0.170	2.798	0.006*	H1c	Yes
	TC	0.118	1.516	0.131	H1d	\
PA	CB	−0.057	0.642	0.522	H1e	\
	PA In	0.170	2.281	0.023*	H1f	Yes
	PA SE	0.180	2.718	0.007*	H1g	Yes
	TC	0.164	1.813	0.071	H1h	\
Dietary In	CB	−0.394	6.608	<0.001*	H2a	Yes
PA In		−0.559	10.369	<0.001*	H2b	Yes
Dietary SE	TC	0.417	7.067	<0.001*	H2c	Yes
PA SE		0.420	7.122	<0.001*	H2d	Yes
Perceived stress	Diet	−0.370	6.397	<0.001*	H3a	Yes
	PA	−0.257	4.431	<0.001*	H3e	Yes
Well-being	Diet	0.287	4.568	<0.001*	H3b	Yes
	PA	0.103	1.631	0.104	H3f	\
Physical QOL	Diet	0.192	2.942	0.004*	H3c	Yes
	PA	0.062	0.929	0.354	H3g	\
Mental QOL	Diet	0.203	3.211	0.002*	H3d	Yes
	PA	0.187	2.950	0.003*	H3h	Yes

Note: *Indicates statistically significant results.
Abbreviations: CB, compensatory belief; CCAM, compensatory carry-over action model; In, intention; PA, physical activity; QOL, quality of life; SE, self-efficacy; TC, transfer cognition.

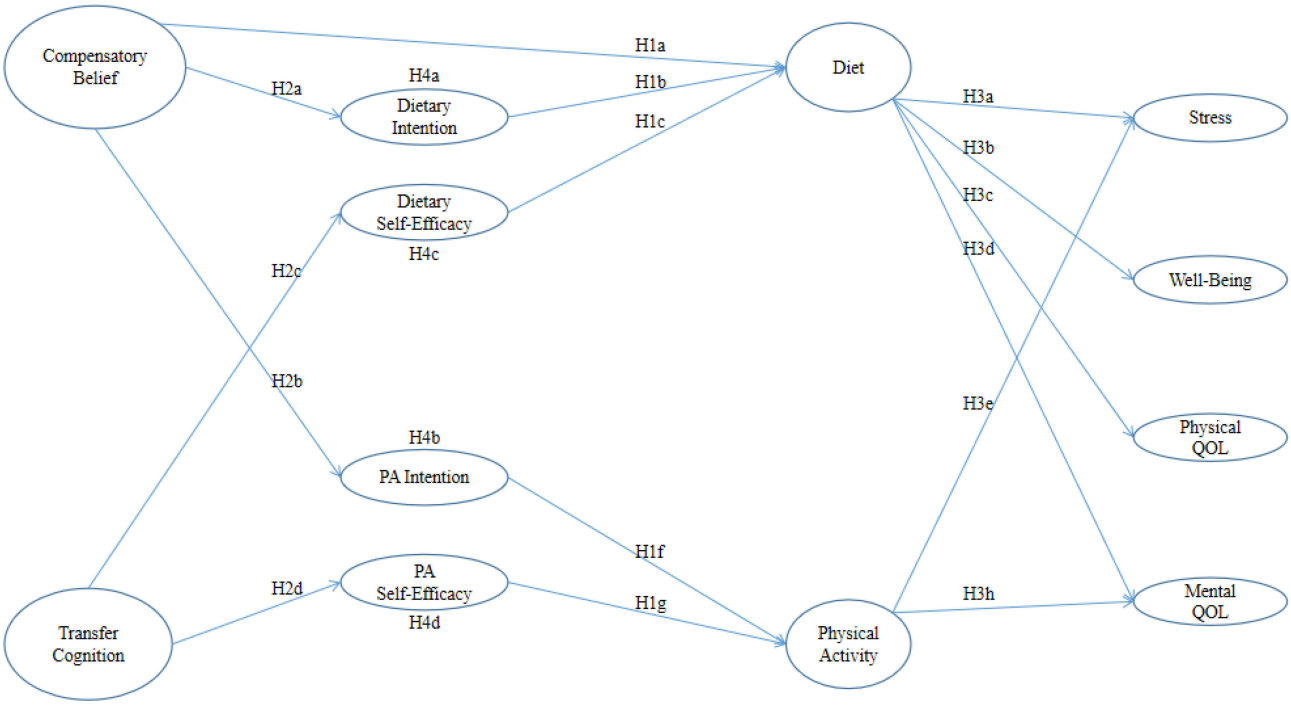

Figure 2 Adjusted hypothetical paths in the preliminary verified model. H1a indicates hypothesis 1a; the other hypotheses were designated in the same way.
Abbreviations: PA, physical activity; QOL, quality of life.

Interrelationships Among Cognitive Factors, Behaviors, and Subjective Outcomes

The maximum likelihood method was used for parameter estimation. Table 5 presents the results of model fitting indicator values and reference values. The results suggested that the revised model fitted well. Table 6 presents the results of path analysis based on SEM. In hypothesis 1, among the antecedent cognitive factors, only CB had a significant effect on diet (H1a, $p<0.001$), and the paths of the other antecedent cognitions that influenced behaviors were eliminated based on the results of the linear regression model (H1d,e,h). Both intention and self-efficacy formed direct associations with their corresponding behaviors (H1b,c,f,g, $p<0.05$), which was consistent with the assumptions of other classical behavioral theories.[11,33] In hypothesis 2, CB exerted significant effects on intention, and TC exerted significant effects on self-efficacy (H2a-d, $p<0.001$), which were consistent with the original hypotheses in CCAM. In hypothesis 3, PA demonstrated significant influence only on perceived stress (H3e, $p=0.004$), and the path of PA to mental aspects of QOL was non-significant (H3h, $p=0.077$), and the remaining paths (H3f, H3g) were eliminated based on the results of the linear regression model. By contrast, diet demonstrated significant effects on all subjective outcomes (H3a-d, $p<0.05$). Figure 3 shows the standardized path coefficients in CCAM.

Table 7 presents the results of mediating effects of cognitive factors on behaviors (hypothesis 4). We used the bootstrap method involving 5000 repeated iterations in AMOS to analyze the mediation effects. All 95% confidence intervals of the indirect effect estimate did not include 0, which suggested that all mediating effects were significant (H4a-d, $p<0.05$). Considering the previous results of hypothesis analyses (H1a,d,e,h), it can be judged that intention exerted partial mediating

Table 5 Results of Model Fitting Indicator Values and Reference Values

Fit index	χ^2/df	RMSEA	GFI	AGFI	CFI
Test result	2.449	0.074 (95% CI=0.070–0.079)	0.937	0.910	0.864
Criterion	<3	<0.08	>0.9	>0.9	>0.8

Abbreviations: AGFI, adjusted goodness-of-fit index; CFI, comparative fit index; CI, confidence interval; GFI, goodness-of-fit index; RMSEA, root mean square error of approximation.

Table 6 Results of Path Analysis Using CCAM

Category of Hypothesis	Regression Path	Standardized Estimate	|C.R.|	*P*	Hypothesis Established
H1: Influence of cognitive factors on behavior	H1a: CB→Diet	−0.406	4.786	<0.001	Yes
	H1b: Dietary In→Diet	0.174	2.312	0.021	Yes
	H1c: Dietary SE→Diet	0.324	4.426	<0.001	Yes
	H1f: PA In→PA	0.385	6.293	<0.001	Yes
	H1g: PA SE→PA	0.204	3.399	<0.001	Yes
H2: Influence of antecedent cognition on mediated cognition	H2a: CB→Dietary In	−0.427	5.531	<0.001	Yes
	H2b: CB→PA In	−0.558	8.735	<0.001	Yes
	H2c: TC→Dietary SE	0.428	6.798	<0.001	Yes
	H2d: TC→PA SE	0.423	6.766	<0.001	Yes
H3: Influence of behavior on subjective health outcomes	H3a: Diet→PS	−0.282	3.996	<0.001	Yes
	H3b: Diet→WB	0.718	6.682	<0.001	Yes
	H3c: Diet→Physical QOL	0.164	2.243	0.025	Yes
	H3d: Diet→Mental QOL	0.400	4.987	<0.001	Yes
	H3e: PA→PS	−0.203	2.880	0.004	Yes
	H3h: PA→Mental QOL	0.108	1.767	0.077	No

Notes: H1a refers to hypothesis 1a; the other hypotheses were designated in the same way.
Abbreviations: CB, compensatory belief; CCAM, compensatory carry-over action model; In: intention; PA, physical activity; PS, perceived stress; QOL, quality of life; SE, self-efficacy; TC, transfer cognition; WB, well-being.

effects on the relationship between CB and diet (H4a) and exerted complete mediating effects on the relationship between CB and PA (H4b); self-efficacy exerted complete mediating effects on the relationship between TC and diet (H4c) and between TC and PA (H4d).

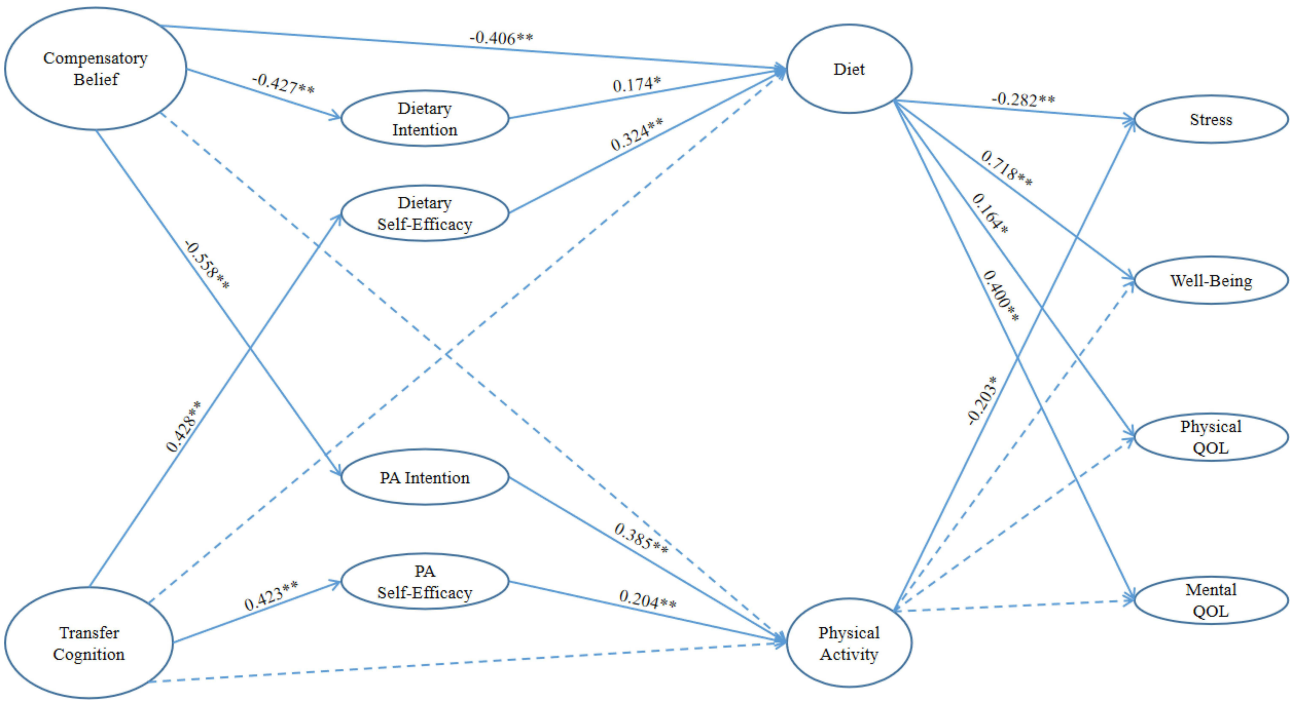

Figure 3 Standardized path coefficients in the compensatory carry-over action model. *P<0.05, **P<0.001. The dotted lines indicate non-significant results.
Abbreviations: PA: physical activity; QOL: quality of life.

Table 7 Results of Mediating Effects of Cognitive Factors on Behaviors

Path	Indirect Effect Estimate	95% CI	*P*	Hypothesis Established
H4a: CB→Dietary In→Diet	−0.240	−0.474 to −0.119	0.006	Yes
H4b: CB→PA In→PA	−486.509	−782.908 to −295.330	0.007	Yes
H4c: TC→Dietary SE→Diet	0.149	0.043 to 0.326	0.009	Yes
H4d: TC→PA SE→PA	196.530	33.029 to 402.254	0.015	Yes

Notes: H4a refers to hypothesis 4a; other hypotheses were designated in the same way.
Abbreviations: CB, compensatory belief; CI: confidence interval; In: intention; PA, physical activity; SE, self-efficacy; TC, transfer cognition.

Discussion

This study evaluated the relationships and mediating effects between cognitive factors and diet or PA during the post–bariatric surgery period, explored the effects of diet and PA on subjective health outcomes, and attempted to identify the hypothetical paths using CCAM through an empirical study. This study represents the first complete validation of hypotheses using CCAM. Originally designed for managing obesity or diabetes, CCAM aims to understand the relationship between diet and PA for more effective prevention or management of these conditions.[16] Given that bariatric surgery patients typically belong to the severely obese population, with a high prevalence of diabetes,[4] decoding their behaviors post-surgery using CCAM holds significant clinical implications for lifestyle management. According to the results, the SEM showed an excellent fitting, confirming the effectiveness of most path relationships between cognitive factors and behaviors in CCAM. Core cognitive factors (CB, TC, intention, and self-efficacy) assessed using CCAM were associated with individual cognitions and attitudes towards diet and PA. This implies the possibility of explaining the interaction between diet and PA through cognitive factors.

Our study also found that the intentions and self-efficacy regarding diet and PA influence their respective behaviors, consistent with previous research in bariatric surgery based on behavioral change theories. Zhu et al[33] investigated factors affecting dietary compliance post-bariatric surgery using the Attitude-Social influence-Efficacy Model, and reported that dietary intention, attitude, and self-efficacy were primary predictors of dietary compliance. Ren et al[34] conducted a randomized controlled trial of exercise intervention in patients after bariatric surgery based on Cross-theoretical Model. They evaluated patients' exercise self-efficacy and intention, identifying stages of behavioral changes to implement targeted interventions and improve exercise compliance.

Regarding antecedent cognitions, both CB and TC primarily exerted their impact on intention and self-efficacy, but most of their influencing paths had no significant direct relationship with behaviors, and only CB had a negative effect on diet. Previous studies have noted behavioral compensation in diet[35] and other behaviors including alcohol consumption, sedentary behavior, and smoking.[21,22] CB is a cognitive coping strategy used to alleviate guilt arising from unhealthy behaviors by engaging in compensatory healthy behaviors.[15] Many bariatric surgery patients exhibited unhealthy dietary behaviors, such as overeating and grazing. The effects of weight loss caused by the surgery are usually extremely significant in the early postoperative period, some patients engaging in PA (such as walking or swimming) but exhibiting suboptimal dietary control may perceive that "weight loss continues due to participation in PA, even with occasional dietary lapses",[36] this perception leads to an elevation in CB, further exacerbating dietary behaviors. Concurrently, poor dietary habits may attenuate CB's direct effect on PA. This might explains why CB negatively affects only the intention of PA, while influencing both dietary behavior and intention. TC, originating from pedagogy research, has gained increasing attention in health behavior management.[37] A systematic review revealed that individuals engaged in optimal exercise levels are more motivated to enhance their eating behavior.[38] Based on this finding, Fleig investigated TC's influence on factors within the HAPA theory, finding that TC affects self-efficacy, with high TC levels associated with frequent use of self-regulation strategies.[39] However, post-bariatric patients typically exhibit suboptimal diet and PA behaviors, and the behavior management requirements during follow-up may deplete patients' willpower. This may limit TC's positive effect on behaviors to self-efficacy rather than directly impacting behaviors.

We analyzed the mediating effects of antecedent cognitions on behaviors. Except for the CB and diet relationship (H4a), intention and self-efficacy were found to be complete mediators in the relationship between antecedent cognitions

and behaviors in the other three hypotheses (H4b, H4c, and H4d). This suggested that intention and self-efficacy play crucial roles in mediating the influence of CB or TC on behaviors, and interventions targeting individual CB or TC may affect behaviors primarily in the pre-contemplation or contemplation stage. Particularly, intention partially mediated the CB and diet relationship, possibly due to patients' poor dietary status postoperatively, leading to the activation of CB when patients refused to correct their unhealthy dietary habits.[35] This implies that implementing intervention measures to inhibit CB could enhance dietary behavior during the post–bariatric surgery period. Moreover, interventions targeting CB and TC can benefit individuals requiring multiple health behavior changes, such as bariatric surgery patients, due to their indirect associations with multiple behaviors. During the early postoperative period, healthcare providers can educate patients about the prevalence and adverse effects of "compensatory eating" by providing negative examples (eg, patients frequently consume high-sugar snacks after exercise as compensation, leading to excessive calorie intake exceeding energy expenditure from PA and hindering weight loss), aiming to suppress patients' CB.[15] TC can be enhanced by adjusting the order of behavioral management. Engaging in exercise can foster individual motivation and confidence in dietary control, while increasing fruit and vegetable intake or reducing sweets consumption can promote patients' interest in PA.[40] In practical interventions, TC's carry-over effects can be maximized based on patient preferences. For instance, patients inclined towards walking can be encouraged to consume fruits and vegetables following their activities, thus reinforcing their exercise enthusiasm.

Regarding the impact of behaviors on subjective health outcomes, diet significantly influenced perceived stress, well-being, and QOL, whereas PA only affected perceived stress. This discrepancy may stem from the extensive changes in gastrointestinal tract structure after bariatric surgery.[41] Adherence to dietary guidelines not only facilitates rapid weight loss but also reduces gastrointestinal symptoms like vomiting and acid reflux, leading to an improved weight loss experience.[33] The main purpose of postoperative PA is to enhance energy expenditure and prevent muscle loss, thereby improving body composition. However, PA-induced weight loss often requires a long time to be effective, and most of patients do not regularly engage in PA. Consequently, the subjective benefits derived from energy dissipation through PA are limited.[42] Our study focused on psychological outcomes, and dietary behavior was also a primary determinant in obesity studies with physiological status as main outcomes. In Gils et al's study,[24] regardless of whether the patients engaged in PA, those who adhered to the Mediterranean diet achieved more weight loss than those who adhered to PA alone during the short-term after bariatric surgery. Similarly, Brown et al's factorial control trial[43] in obese breast cancer patients found that those adhering to a controlled diet alone or combined with exercise achieved significant fat loss compared to those with uncontrolled behaviors, while exercising alone had limited effects on body weight.

In summary, valid paths in CCAM suggested that interventions targeting cognitive factors, particularly through dietary modifications, are easier and more effective. Inhibiting compensatory eating behaviors may promote overall behavioral patterns, potentially leading to improved PA levels and a better weight loss experience for patients. The link between behaviors and subjective health outcomes highlights that diet played a more significant role in overall health than PA during the postoperative period. Therefore, from the perspective of joint promotion of behaviors after bariatric surgery, prioritizing dietary intervention over PA is advisable based on CCAM analysis. During intervention, besides focusing on intention and self-efficacy, managing antecedent cognitions including CB and TC may positively influence the cooperative promotion of diet and PA. In particular, inhibiting CB levels may hold greater importance.

Previous studies have also examined the diet and PA interactive relationship at a physiological level. Hazell et al[44] found that exercise-induced muscle metabolism can lead to changes in cytokine release, insulin concentration, and lactic acid production, which may mediate alterations in anorexia signal peptide tyrosine-tyrosine and glucagon-like peptide-1. Consequently, changes in appetite hormones further suppress ghrelin levels, prolonging eating latency and reducing energy intake. A meta-analysis revealed that low-intensity exercise accelerated gastric emptying, leading to higher subsequent energy intake. However, when exercise intensity exceeded 70% VO_2 max, gastric emptying was delayed, potentially contributing to post-exercise appetite suppression.[45] Regarding the impact of diet on PA, Castro et al[46] found in their randomized controlled trial that obese patients receiving a very low-calorie ketogenic diet exhibited increased PA levels during the intervention. Diet composition also affected subsequent PA time. Bray et al[47] found that when additional energy intake came from fats, there was no increase in 24-hour energy expenditure (24EE), whereas excess dietary protein intake notably stimulated 24EE and increased energy expenditure during sleep. Many studies have

elucidated the physiological mechanisms and mediating factors through which PA affects diet, but the reciprocal effect of diet on PA remains unclear. Our study investigated this behavioral interaction at the psychological level, revealing that cognitive factors, particularly CB, mediated the impact of diet on PA, which may help explain the balance between energy intake and subsequent energy expenditure.

This study has several limitations. Firstly, this was a cross-sectional study, hence we were unable to obtain the baseline status of cognitive factors and behaviors, nor observe how these variables changed at 3 months postoperatively, so the applicability of our results is primarily optimal at this time point. While psychological research has indicated that personality traits such as cognitive factors exhibit stable consistency throughout an individual's lifespan,[48] future longitudinal studies will still be needed to observe dynamic changes and make stronger causal inferences. Secondly, our study measured overall dietary compliance and various durations of PA post-bariatric surgery, but did not differentiate dietary composition or types of PA. Thirdly, while this study's theoretical basis mainly drew from research on bariatric surgery populations in Europe and America, we did not adequately account for the dietary habit disparities between Eastern and Western populations. This oversight may introduce potential cultural bias and impact the generalizability of the results. Finally, CB and TC were core variables in the CCAM, and this study and previous research mainly focused on their impact on behaviors. However, CB and TC measurement relied on patients' personal attitudes towards behaviors. Therefore, future studies should further investigate how behaviors influence CB and TC to better understand behavioral patterns post-bariatric surgery and enhance behavioral interventions accordingly.

Conclusion

Drawing from the framework of CCAM, this study utilized SEM to examine the interplay between behavioral cognitive factors, diet, PA, and subjective health outcomes among post-bariatric surgery patients. Given the suboptimal behavioral patterns observed after surgery, prioritizing dietary interventions over PA interventions is recommended for maximizing behavioral synergies and optimizing subjective health outcomes. Notably, the carry-over effect of TC did not directly impact patient behaviors, underscoring the importance of targeting CB inhibition in interventions. Patients should be educated about forming correct cognitive views about dietary recommendations after bariatric surgery, discovering behavioral compensation tendency, reducing the extent of damage of CB to behavioral patterns, consolidating the weight loss effects of bariatric surgery with positive healthy behaviors, and avoiding the occurrence of re-obesity.

Abbreviations

24EE, 24-hour energy expenditure; AGB, adjustable gastric banding; BAROS, bariatric analysis and reporting outcome system; BMI, body mass index; CB, compensatory belief; CCAM, compensatory carry-over action model; EWL%, excess weight loss rate; HAPA, health action process approach; MCS, mental component summary; MET, metabolic equivalent; PA, physical activity; PCS, physical component summary; QOL, quality of life; RYGB, Roux-en-Y gastric bypass; SEM, structural equation model; SG, sleeve gastrectomy; TC, transfer cognition.

Data Sharing Statement

The dataset are available from the corresponding author (Qin Xu) or the first author (Kang Zhao) upon reasonable request and with permission of School of Nursing, Nanjing Medical University.

Ethics Approval and Consent to Participate

This study adhered to the principles outlined in the Declaration of Helsinki. The ethics review committee of the First Affiliated Hospital of Nanjing Medical University approved this study (2021-SR-031). All patients who accept to participate signed the written informed consent.

Consent for Publication

We have obtained consent to publish from the participant to report individual patient data.

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Author Contributions

All authors made a significant contribution to the work reported, whether that is in the conception, study design, execution, acquisition of data, analysis and interpretation, or in all these areas; took part in drafting, revising or critically reviewing the article; gave final approval of the version to be published; have agreed on the journal to which the article has been submitted; and agree to be accountable for all aspects of the work.

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Disclosure

The authors report no conflicts of interest in this work.

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