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Network analysis of interrelationships among physical activity, sleep disturbances, depression, and anxiety in college students

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Abstract

Background Physical activity, sleep disturbances, anxiety, and depression are interrelated, but prior research focused on overall scores, neglecting symptom interactions and triggering effects. This study employed network analysis to explore these connections from a symptom-network perspective.

Methods Physical Activity Scale-3, Pittsburgh Sleep Quality Index Scale, Self-Reating Depression Scale, and Self-Reating Anxiety Scale were conducted on 4683 college students from September to October 2024 by convenience sampling method. Spearman correlation is used to explore the relationship between these variables. Network analysis revealed structural connections between physical activity and sleep disturbances, identifying core and bridge symptoms. Flow network further explored the impacts of physical activity and sleep disturbances on depression and anxiety.

Results Physical activity was negatively correlated with sleep disturbances, depression, and anxiety ($p<0.05$), while sleep disturbances was positively correlated with depression and anxiety ($p<0.01$). In the symptom network of physical activity and sleep disturbances, "sleep quality" (EI = 0.009) and "daytime dysfunction"(EI = 0.827) were the core symptoms, while "daytime dysfunction" (BEI = 0.035) and "intensity of physical activity" (BEI = 0.015) were the bridge symptoms. In the flow networks, "physical activity frequency" (r=-0.14) and "daytime dysfunction"(r = 0.13) were particularly correlated with depression. "Sleep disruptions"(r = 0.18) and "physical activity frequency" (r=-0.14) showed a strong correlation with anxiety.

Conclusion The study identified the core and bridge symptoms of the physical activity and sleep disturbances symptom network, as well as key symptoms linked to anxiety and depression. Targeting these symptoms could disrupt their interactions, prevent negative outcomes, and enhance college student well-being.

Keywords Sleep disturbances, Physical activity, Depression, Anxiety, College students, Network analysis

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Background

Contemporary society is undergoing an epochal transformation that profoundly reshapes the lifestyle patterns of college students. Their daily life, learning, social interaction, and entertainment are gradually turning to digital and virtual and showing a high degree of static and unified characteristics. While this evolution dramatically expands information access and communication channels, increasing opportunities for social engagement, it concomitantly diminishes physical activity participation. Research indicates that over half of college students exhibit insufficient physical activity levels, a deteriorating trend that has emerged as a paramount public health concern in this century [1]. Low physical activity has had a profound impact on the health of college students, such as obesity, sleep disturbances, mood disorders, cognitive impairments, attention deficits, and poor quality of life [2, 3].

In addition, sleep disturbances are also one of the common problems among college students. Studies show that the prevalence of poor sleep quality among college students is as high as 76% [4]. The prevalence of sleep disturbances has tripled since 2010 [5, 6]. However, physical activity as a non-drug treatment has significant relief for sleep problems. However, the evidence between physical activity and sleep has blurred as research has progressed. Some studies suggest that physical activity is negatively correlated with sleep quality scores, and the higher the level of physical activity, the better the sleep quality [4]. Moreover, Xiao et al. found through mediation analysis that physical activity not only has a direct impact on sleep disturbances, but also can indirectly increase the degree of sleep disturbances by influencing individual mobile phone use [7]. Additionally, physiological experimental evidence demonstrates that physical activity enhances cerebral blood flow and stimulates melatonin secretion [8]. As a critical sleep-regulating hormone, melatonin facilitates shortened sleep onset latency and improved sleep quality [8].In contrast, Huang et al. utilized wrist-worn accelerometer data with single-factor models and isotemporal substitution models (ISM) to reveal that only higher levels of light physical activity (LPA), moderate-to-vigorous physical activity (MVPA), and substituting 30 min of sedentary behavior with equivalent durations of MVPA, demonstrated significant improvements in college students' sleep quality [9].In addition, in a recent meta-analysis that included 29 studies with a total of 141,035 participants, the authors found no relationship between physical activity and sleep in college students in targeted studies, and random-effects meta-analyses revealed that only moderate-to-high intensity physical activity was significantly associated with sleep disturbances and only weakly associated with sleep duration [10]. This difference in results may be due to differences in the race of the studies, research tools, etc. Therefore, it is necessary to further explore the relationship between physical activity and sleep disturbances.

Low physical activity and the prevalence of sleep disturbances have important effects on the mental health of college students [11, 12]. Anxiety and depression have become the main mental health problems of college students [13]. Chen et al. used PHQ9 and GAD7 to investigate college students and found that the prevalence of depression and anxiety among college students was as high as 50.6% and 38.3% during the epidemic period [14]. However, substantial evidence indicates that physical activity is a crucial factor influencing anxiety and depression. A meta-analysis revealed that physical activity exerts a moderate effect size in improving clinical depressive symptoms [15]. Snedden et al. prospectively evaluated the mental health of undergraduate students and undergraduate athletes, and the results revealed that people with higher levels of physical activity had more positive mental health [16].Yu et al. employed structural equation modeling (SEM) to survey 600 college students, discovering that physical activity enhances life satisfaction and psychological resilience in this population, which further improves their emotional reactivity [17]. Notably, the enhancement of emotional reactivity has been confirmed to directly influence their emotional experiences. At the same time, wu et al. conducted a longitudinal study using the International Physical Activity Questionnaire and found that physical exercise has a negative impact on anxiety, which is realized through psychological resilience, and its impact on anxiety is stable across time [18]. Li et al. further corroborated this finding using machine learning, conducting a survey among 2,419 adolescents. Their study revealed that physical activity emerged as one of the critical predictors of adolescent depression, with an AUC value of 0.95, predictive accuracy of 90.52%, and an accuracy rate of 92.01% [19].In addition, physical activity may also improve depression and anxiety by improving cognitive function [20]. A longitudinal study involving 1,722 participants revealed that higher levels of physical activity exert a protective effect on episodic memory [21]. This is attributed to the influence of physical activity on hormonal homeostasis, a critical factor influencing hippocampal function. The hippocampus plays a central role in various processes, such as cognitive processing and emotional regulation [22].In addition, there is also a complex relationship between sleep disturbances and anxiety and depression. On the one hand, sleep disturbances are a serious manifestation of depression and anxiety. More than 90% of people with depression and more than 70% of people with anxiety complain of sleep problems [23, 24]. Additionally, Tonon's research yielded similar findings, where adolescents were categorized into low depression risk, high depression risk, and depressive episode groups. The study revealed that adolescents in the high depression risk and depressive episode groups experienced more severe insomnia, greater social jetlag, and shorter sleep duration compared to those in the low depression risk group [25]. A review also highlighted that patients with depression and anxiety exhibit abnormal eye movement cycles, such as a reduction in slow-wave sleep and disinhibition of rapid eye movement sleep, both of which lead to decreased sleep duration [26]. In addition, patients with depression and anxiety have low responsiveness of the norepinephrine system and abnormal secretion of serotonin, and these two hormones can further interfere with the sleep-wake cycle and exacerbate sleep disturbances in patients [27, 28]. On the other hand, sleep disturbances serve as a contributing factor to depression and anxiety, with severe cases increasing the risk of suicidal behavior [29]. A correlation analysis revealed a strong positive association between insomnia and depression, indicating that higher levels of insomnia correspond to more severe depressive symptoms [11]. Palmer et al. conducted a meta-analysis of 154 studies from nearly 50 years and found that any form of sleep disturbances can lead to a decrease in positive emotions, a decrease in arousal of emotional stimuli, and an increase in negative emotions [30]. Asarnow assigned participants to either a sleep and circadian rhythm intervention group or a psychoeducation group, providing six 50-minute intervention sessions. The results indicated that participants in the sleep and circadian rhythm intervention group exhibited the fastest and most significant improvement in depressive symptoms [31]. Similarly, Memon utilized a randomized controlled trial to investigate the impact of cognitive behavioral therapy for insomnia on major depression and generalized anxiety, finding that CBT-I was more effective for psychiatric patients with comorbid sleep disturbances [10]. These findings further elucidate the positive effects of sleep improvement on depression. Concurrently, the social zeitgeber theory provides evidence that the onset of depression and anxiety arises from the disruption of environmental "temporal cues" by significant life events, which affect circadian rhythm regulation, primarily manifested as disorder in sleep schedules [32]. Collectively, these studies illustrate the reciprocal relationship between sleep and depression, corroborating the findings of Roberts' research [33].

Previous studies predominantly employed traditional analytical methods such as mediation and regression analysis to investigate relationships among physical activity, sleep disturbances, depression, and anxiety. These approaches typically rely on total scale scores and assume variable independence, thereby neglecting interactive and triggering effects between distinct symptoms. As a novel statistical approach, network analysis compensates for these limitations. It enables exploration of relationships between physical activity and sleep disturbances from a symptom-network perspective. By calculating network topology and centrality metrics, we can identify core symptoms and bridge symptoms within the network. Furthermore, the construction of the flow network further examined the direct and indirect impacts of symptoms on adverse outcomes, which helps us better analyze the relationships between variables and also provides support for the implementation of precise intervention. However, it should be noted that all the variables in this study were measured through scales and were not clinical diagnoses. Therefore, our primary research objectives are as follows: (1) To investigate the relationships among physical activity, sleep disturbances, depression, and anxiety; (2) To identify the network structure and characteristics of physical activity and sleep disturbances through network analysis; (3) To construct flow networks for depression and anxiety, and explore the direct or indirect effects of physical activity and sleep disturbances symptom clusters on these conditions. Research Hypotheses are: Hypothesis (1) Physical exercise is significantly negatively correlated with sleep disturbances, depression, and anxiety; sleep disturbances are significantly positively correlated with depression and anxiety. Hypothesis (2) The factors of physical exercise and sleep disturbances are not independent but interconnected, forming a relational network. Hypothesis (3) Physical exercise and sleep disturbances factors exert direct or indirect negative impacts on depression and anxiety.

Materials and methods

Participants and procedures

According to previous research, the sample size for network analysis should be no less than the sum of threshold parameters and pairwise association parameters. Threshold parameters represent the number of nodes in the network, while the pairwise association parameters = the total number of nodes ×(total number of nodes − 1)/2 [34]. Since this network comprises 10 nodes, a minimum sample size of 55 participants is required. However, to ensure the stability and accuracy of the network, it is advisable to include 3–5 times the minimum sample size [24]. Therefore, this study expanded the minimum sample size to 275 participants.

This study employed a convenience sampling method and conducted a survey among college students from three universities in china, between September and October 2024 via the Wenjuanxing platform. Inclusion criteria: (1) Currently enrolled college students; (2) Aged between 16 and 26 years [35]; (3) Voluntarily participated in this survey. Exclusion criteria: (1) Individuals with severe mental disorders or organic diseases (assessed through the question: "Do you have severe mental disorders or organic diseases such as moderate depressive disorder, schizophrenia, or severe traumatic brain injury?"); (2) Participants with an average response time per questionnaire item of less than 2 s [35]. Ultimately, data from 4,683 participants were included in the analysis.

Measurement

Demographic information

The general demographic information of college students surveyed in this study includes age, gender, whether one is an only child, and ethnicity.

Physical activity

In this study, the Physical Activity Scale-3 (PARS-3) was used to measure college students' physical activity levels. The scale was developed by Liang Deqing and consists of three items assessing physical activity intensity, duration, and frequency [36]. Physical activity intensity was measured using a 5-point rating scale (1 = capable of very Light exercise; 2= capable of low-intensity but non-strenuous exercise; 3 = capable of moderate-intensity exercise; 4 = capable of high-intensity but non-sustained exercise; 5 = capable of high-intensity and sustained exercise), with higher scores indicating greater activity intensity. Physical activity duration was assessed through a 5-point rating system (1 = ≤ 10 min; 2 = 11–20 min; 3 = 21–30 min; 4 = 31–59 min; 5 = ≥ 60 min), where higher scores reflected longer physical activity duration.Physical activity frequency employed a 4-point rating method (1 = ≤ 1 time/month; 2 = 2–3 times/month; 3 = 1–2 times/week; 4 = 3–5 times/week; 5 = 1 time/day), with higher scores indicating more frequent physical activity.The total scale score was calculated as the product of the three dimensional scores, ranging from 0 to 100. Higher scores represented greater physical activity levels among participants. In this study, the Cronbach's α coefficient for this scale was 0.676, indicating acceptable internal consistency.

Sleep disturbances

In this study, the Pittsburgh Sleep Quality Index Scale (PSQI) was used to assess college students' sleep status. Developed by Buysse et al. [37]. The scale comprises 18 items distributed across 7 dimensions: subjective sleep quality, sleep latency, sleep duration, habitual sleep efficiency, sleep disruptions, hypnotic medication use, and daytime dysfunction [7, 38]. Each dimension is scored on a 0–3 scale, with higher scores indicating greater severity of the corresponding symptom. The total scale score, calculated as the sum of the seven dimensions, ranges from 0 to 21, where higher scores reflect more severe sleep disturbances [39]. The Cronbach's α coefficient for this scale in the current study was 0.94.

Depression

This study employed the Self-Rating Depression Scale (SDS) to evaluate depressive symptoms among college students. Developed by William W.K. Zung [40, 41], the scale comprises 20 items designed to assess depression experienced in the past week. Participants rated the frequency of symptom occurrence for each item using a 4-point Likert scale (from1 = none or very Little of the time to 4= most of the time). The raw score was calculated as the sum of all 20 item scores. This raw score was converted to a standard score by multiplying it by 1.25, resulting in a standard score range of 25–100. A standard score exceeding 53 indicates a depressive state, with higher scores reflecting greater severity of depression [41]. Statistical analyses in this study utilized the standard score. The scale demonstrated excellent internal consistency with a Cronbach's α coefficient of 0.905.

Anxiety

This study utilized the Self-Rating Anxiety Scale (SAS) to assess anxiety levels among college students over the past week. Developed by William W.K. Zung, the scale comprises 20 items, each rated on a 4-point Likert scale based on symptom frequency (from 1 = none or very Little of the time to 4= most of the time) [42]. The raw score is calculated by summing the scores of all 20 items. This raw score is converted to a standard score by multiplying it by 1.25, yielding a standard score range of 25–100. Higher standard scores indicate greater anxiety severity, with scores exceeding 50 considered clinically significant [42]. Statistical analyses in this study employed the standard score. The scale demonstrated strong internal consistency with a Cronbach's α of 0.871.

Statistical analysis

This study utilized SPSS 29.0 and R 4.4.2 for data analysis. Initially, we conducted Harman's single-factor test using SPSS 29.0 to examine whether the data exhibited severe common method bias. Due to the non-normal distribution of the data, we used M (P25, P75) to describe the data. Subsequently, Spearman's correlation was used to explore the relationships between variables. Finally, R 4.4.2 was used to perform network analysis from the perspective of symptoms to investigate the relationship between physical activity and sleep disturbances, and flow networks were used to further explore the direct and indirect effects of physical activity and sleep disturbances on depression or anxiety. The steps of network analysis included symptom network estimation, network visualization, network centrality and predictability testing, network accuracy and stability testing, network comparison, and flow network construction.

Symptom network estimated

We used the R package "qgraph" to evaluate the relationship between physical activity and sleep disturbances among college students [35]. First, the Graphical Gaussian Model (GGM) was used to compute the network structure. Second, we simplified the network using the graphical least absolute shrinkage and selection operator (LASSO) and the extended Bayesian information criterion (EBIC) to shrink small correlations to exactly zero and reduce spurious correlations. In this model, the gamma hyperparameter was set to a default value of 0.25 [43–45].

We used the R package "qgraph" to visualize the network [35]. In the network structure, each node represents a symptom, and the line between the two nodes represents their correlation. In this study, blue solid lines represent positive correlations, red dashed lines represent negative correlations, and the thicker the line, the stronger the correlation between the two nodes [46].

Centrality and predictability

According to previous research, when both positive and negative correlations exist in a network, expected influence and bridge expected influence are more representative than centrality indicators such as strength and bridge strength [35]. Therefore, in this study, expected influence was used to evaluate the influence of each node, with higher values indicating greater influence of the node. Based on previous studies, we identified the two symptoms with the highest expected influence values as the core symptoms of the network [47]. Additionally, we calculated the predictability of each node using the "mgm" package. This is represented by a circular pie chart on the outside of each node, with larger values indicating a greater degree to which the node can be influenced by other nodes [35]. Furthermore, since the network structure of physical activity and sleep disturbances includes symptoms from different disease groups, it is necessary to identify bridge symptoms in the network. Therefore, we calculated the bridge expected influence of each node, with higher values indicating stronger information transmission ability of the node across different disease groups. There are two ways to calculate bridge expected influence: bridge expected influence (1-step) and bridge expected influence (2-step) [48]. In this study, following previous research, bridge expected influence (1-step) was included in the analysis [49]. According to Jones, we identified nodes with bridge expected influence values in the top 20% as bridge symptoms [50].

Accuracy and stability of the network

In this study, we used the "bootnet" package in R to evaluate the stability and accuracy of the network [43]. During this process, the stability coefficient (CS-C) of expected influence and bridge expected influence was calculated to quantify network stability. CS-C refers to the maximum sample size that can be reduced while maintaining a correlation of at least 0.7 between the centrality measures of the original sample and the reduced sample. Generally, a CS-C greater than 0.25 indicates sufficient stability of the network, greater than 0.5 indicates good stability and greater than 0.7 indicates excellent stability [51]. Additionally, we used non-parametric bootstrapping to assess the bootstrap confidence interval (95% CI), with narrower confidence intervals indicating higher accuracy of the network [35].

Network comparison

Building on this, we further explored whether network characteristics differed between genders [49]. We performed the Network Comparison Test (NCT) using the R package "NetworkComparisonTest" [35]. We compared three aspects of the networks between different genders. First, we examined whether there were differences in the overall structure of the two groups' networks by comparing the distribution of edge weights. Next, we used the global strength invariance test to compare the connectivity of the two networks. Finally, we analyzed whether there were differences in the strength of a specific edge in the two networks using the edge invariance test, and we corrected the p-values using the Bonferroni-Holm method [52].

Construction of flow network

While symptom networks effectively reveal complex interrelationships among individual symptoms, they lack the capacity to differentiate between direct and indirect influence pathways. In contrast, flow networks provide a more intuitive visualization of variables associated with adverse outcomes through both direct and indirect connections, enabling the identification of symptoms with greater impact based on edge weight magnitudes. To investigate the effects of physical activity and sleep disturbances on depression and anxiety, we incorporated "depression" and "anxiety" variables into the network framework and employed the "flow" function for network construction and visualization [53]. In this network representation, each node corresponds to a specific symptom, with edge thickness indicating the strength of correlation between nodes. The rightmost node denotes the adverse outcome. Direct connections between a node and the outcome indicator signify direct influence, while absence of direct connection implies indirect influence. This approach allows for systematic analysis of symptom interactions and their pathways of impact.

Table 1 Descriptive statistics and correlation analysis

variable	M(P25、P75)	1	2	3	4
1 SDS	46.00(36.00,58.00)	1			
2 SAS	40.00(34.00,48.00)	0.786**	1		
3 PSQI	4.00(2.00,6.00)	0.442**	0.493**	1	
4 PARS-3	4.00(1.00,12.00)	−0.110**	−0.089**	−0.035*	1

SDS Self-Rating Depression Scale; *SAS* Self-Rating Anxiety Scale; *PSQI* Pittsburgh Sleep Quality Index Scale; *PARS*-3 Physical Activity Scale-3; *P<0.05,**P<0.01

Results

Common method bias test

Our study employed Harman's single-factor test to assess common method bias. The first factor was found to explain 29.48% of the total variance, which is below the critical threshold of 40% [54]. This indicates that common method bias is not severe.

Study sample

A total of 4,683 college students were included in this study, with an average age of 20.33 ± 1.27 years. Among them, 1,462 (31.2%) were male and 3,221 (68.8%) were female. The majority were Han Chinese (4,306, 91.90%) and came from urban areas (2,900, 61.90%). More than half of the students were non-only children (2,427, 51.80%). The prevalence rates of sleep disturbances, depression, and anxiety were 17.6%, 35.04%, and 21.82%, respectively.

Descriptive statistics and correlation analysis

As shown in Table 1, physical activity scores were significantly negatively correlated with depression, anxiety, and sleep disturbances ($p < 0.05$), and sleep disturbances scores were significantly positively correlated with depression and anxiety ($p < 0.01$).

Network structure

Figure 1 presents the network structure of the relationship between sleep disturbances and physical activity among college students. The network consists of a total of 10 nodes, with 33 non-zero edges out of 45 possible edges, resulting in a network density of 73.33%. Among all the edges, the edge strength between P1 (intensity of physical activity) and P2 (duration of physical activity) is the highest ($r = 0.402$), followed by the edge between P2 (duration of physical activity) and P3 (physical activity frequency) ($r = 0.372$), and the edge between S1 (sleep quality) and S2 (sleep latency) ($r = 0.306$).

Network centrality and predictability

Figure 2(A) presents the results of the non-standardized Expected influence (EI) for all nodes in the network.

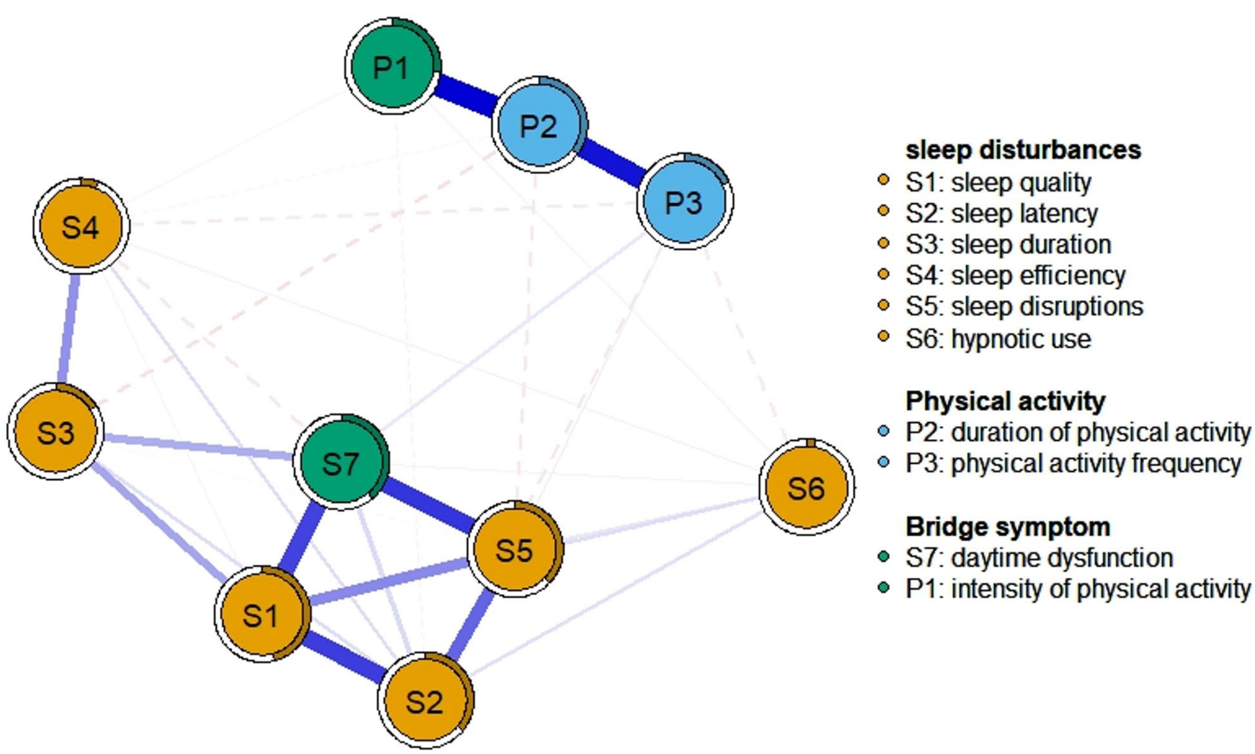

Fig. 1 Symptom network of physical activity and sleep disturbances in college students. Note: Each node represents a symptom, the link between the two nodes represents the relationship between the nodes, the blue solid line represents a positive correlation, the red dashed line represents a negative correlation, the thicker the line segment, the stronger the correlation

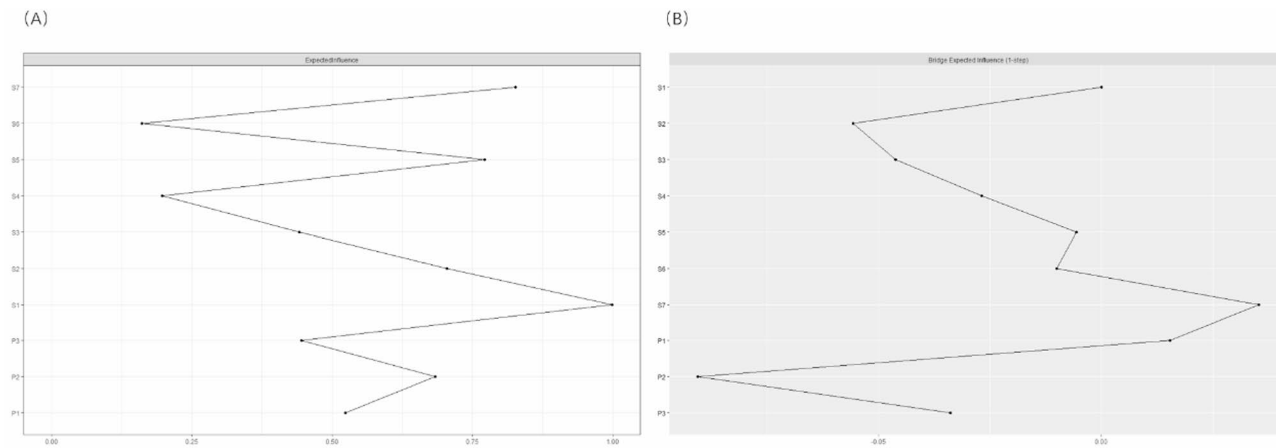

Fig. 2 (**A**) results of non-standardized expected influence estimation for the symptom network of physical activity and sleep disturbances among college students; (**B**) results of non-standardized bridging expected influence estimation for the symptom network of physical activity and sleep disturbances among college students

The results show that S1 (sleep quality) has the highest EI (EI = 0.999) in the network, followed by S7 (daytime dysfunction) (EI = 0.827). This indicates that S1 (sleep quality) and S7 (daytime dysfunction) have a significant influence on the network and are identified as the core symptoms of the network.

The results of the non-standardized Bridge expected influence (BEI) are shown in Fig. 2(B). The node S7 (daytime dysfunction) has the highest BEI (BEI = 0.035), followed by P1 (intensity of physical activity) (BEI = 0.015). This indicates that S7 (daytime dysfunction) and P1 (intensity of physical activity) are the most critical bridging symptoms connecting sleep disturbances and physical activity, with strong information transmission capabilities between different symptom clusters.

The predictability of each node is represented by a circular pie chart outside the node. The average predictability of the network is 0.124, indicating that on average, 12.40% of the variance of each node can be explained by neighboring nodes. Among them, S1 (sleep quality) has the highest predictability of 0.458, followed by S7 (daytime dysfunction) with 0.388. This suggests that 45.80% of the variance in S1 (sleep quality) and 38.80% of the variance in S7 (daytime dysfunction) can be explained by other neighboring nodes.

Network stability and accuracy test

The CS-C coefficients of the expected influence and bridge expected influence of the network were 0.75 and 0.361, respectively, both greater than 0.25, indicating that the network has good stability. The visualization results are shown in Fig. 3. As shown in Fig. 4, the confidence intervals of the bootstrap results of edge weights in the network are very narrow, indicating that the network has good accuracy.

Network comparison

The network comparison test (NCT) was used to evaluate whether there were differences in network characteristics between different genders. The results of the global strength invariance test are shown in Fig. 5(A). There was no significant difference in the global strength of the network between different genders (global strength: 3.332 for males and 3.172 for females, S = 0.160, $P = 0.697$). The results of the network structure invariance test are shown in Fig. 5(B). There was a significant difference in the network structure between different genders (M = 0.178, $P < 0.001$). The results of the edge weight invariance test showed that there was a significant difference in the edge weight between nodes P1 and P2 between different genders (edge weight for males was 0.487 and for females was 0.309, $P < 0.05$).

Construction of flow networks

Figure 6 shows the flow networks of depression and anxiety. We found that in the flow network of depression, all symptoms were directly correlated with SDS except for P1 (intensity of physical activity) and S4 (sleep efficiency), which were indirectly correlated with SDS. Among them, P3 (physical activity frequency) had the strongest correlation with SDS ($r = -0.14$), followed by S7 (daytime dysfunction) ($r = 0.13$). In the flow network of anxiety, all symptoms were directly correlated with SAS, with S5 (sleep disruptions) having the strongest correlation with SAS ($r = 0.18$), followed by P3 (physical activity frequency) ($r = -0.14$).

Discussion

To our knowledge, this is the first study to use network analysis to explore the relationship between physical activity and sleep disturbances among college students and to use flow networks to explore which symptoms

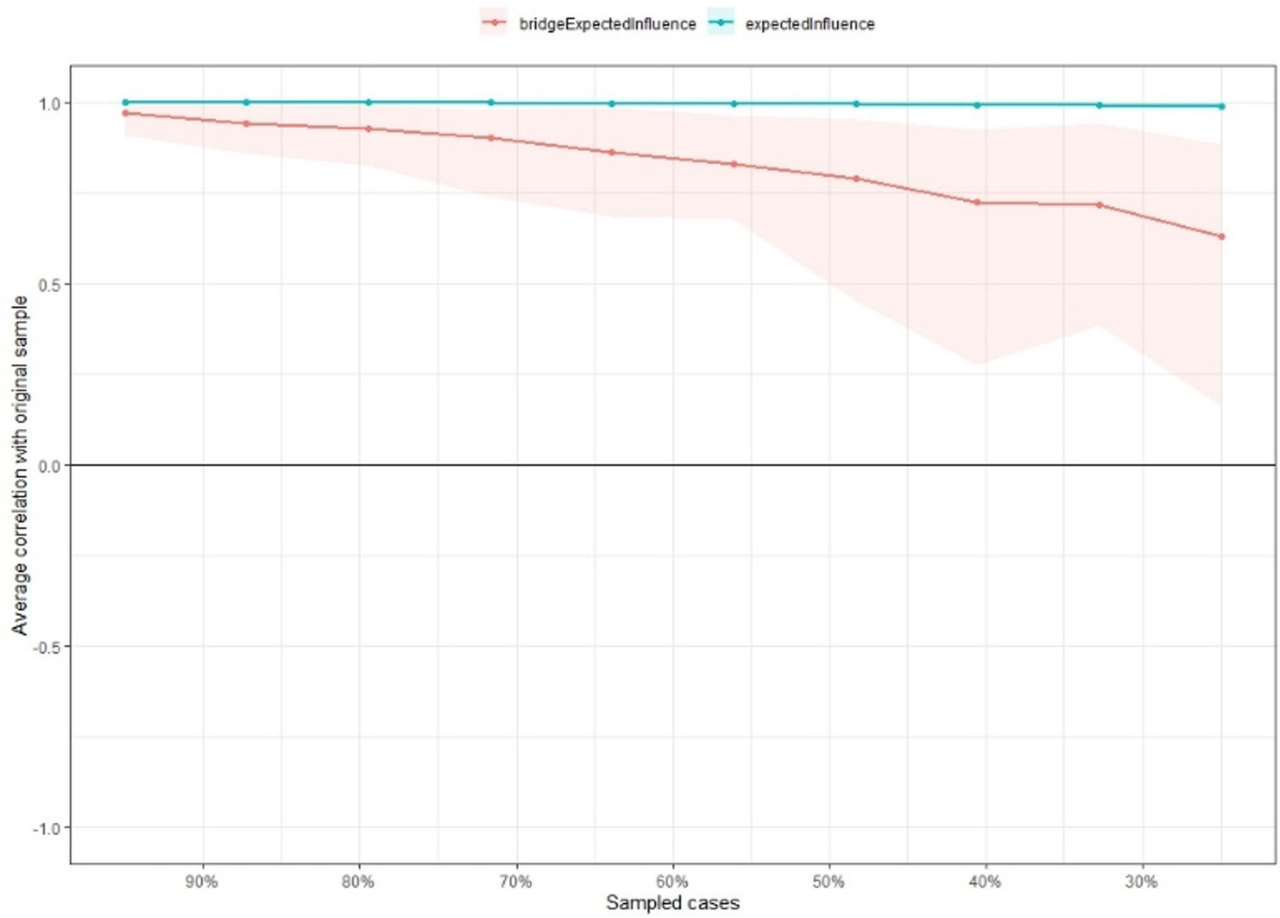

Fig. 3 Visualized results of physical activity and sleep disturbances symptom network stability test in college students. The x-axis indicates the percentage of cases of the original sample included at each step. The y-axis indicates the average of correlations between the centrality indices from the original network and the centrality indices from the networks that were re-estimated after excluding increasing percentages of cases

in physical activity and sleep disturbances have a strong impact on depression and anxiety. This provides support for improving the mental health of college students, and the following are some of our findings.

Correlation analysis revealed a negative correlation between physical activity and depression and anxiety scores. This is consistent with the findings of Casanova's study, which used mendelian randomization to find that for every standard deviation increase in physical activity level, the risk of depression decreased by 15%, and higher levels of sedentary behavior were associated with anxiety (OR = 2.59) [55]. This is because physical activity, as an active intervention, can promote neurobiological adaptations such as synaptic growth, increased hippocampal neurogenesis, and improved inflammatory imbalance, which further maintain, repair, and reorganize the homeostatic processes of impaired circuits in patients with depression and anxiety [56]. Furthermore, we also found a positive correlation between sleep disturbances scores and anxiety and depression scores, which aligns with previous research findings [57]. This phenomenon may be attributed to the disruption of normal monoamine neurotransmitter secretion caused by sleep disturbances, subsequently contributing to the development of depression and anxiety [58]. These findings support Hypothesis 1.

Through network analysis, we identified complex interrelationships between physical activity and sleep disturbances, with a network density of 73.33%, lending support to Hypothesis 2. Centrality analysis revealed that sleep quality and daytime dysfunction emerged as the core symptoms within this network.According to the China Sleep Report 2022 published by the Chinese Academy of Social Sciences, nearly half of college students in China experience poor sleep quality [59], a phenomenon similarly observed in international studies [60]. Sleep quality refers to an individual's subjective and objective evaluation of the depth, continuity, and restorative effects of sleep. We identified that within the symptom network of physical activity and sleep disturbances, sleep quality emerged as the core symptom with the strongest correlation to sleep latency ($r = 0.306$). This finding underscores

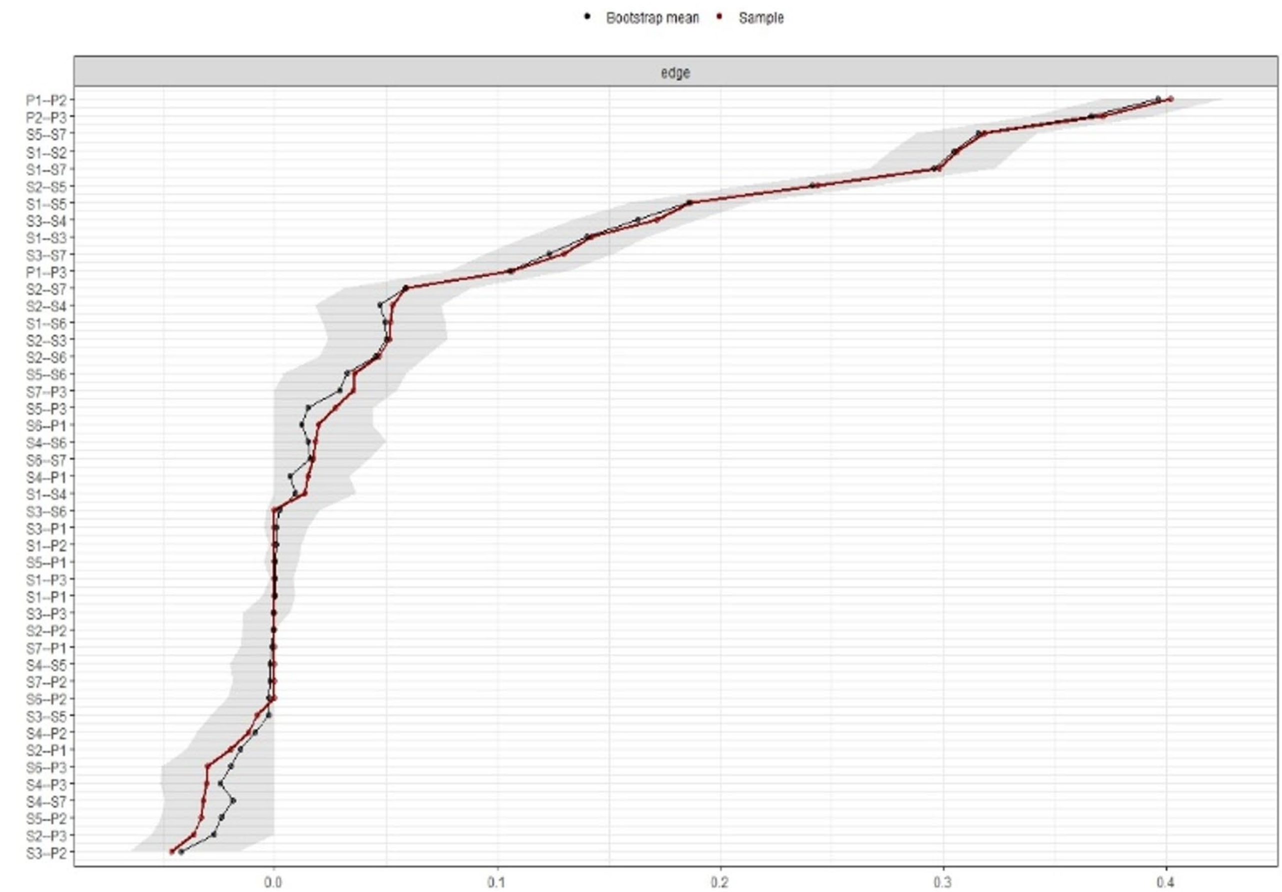

Fig. 4 Results of network accuracy test of physical activity and sleep disturbances symptoms in college students. The red line represents the edge weight value of the sample in this study, and the black line represents the average edge weight value evaluated by the self-service method. The grey area represents the confidence interval calculated by the self-service method. The abscissa represents the regularized partial correlation coefficient, and the ordinate represents the edge in the network

(A) (B)

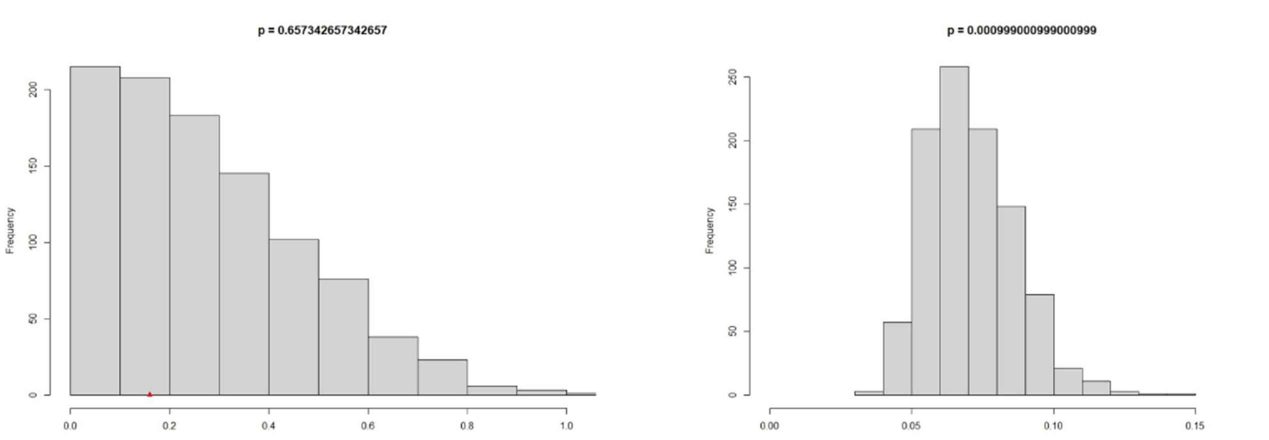

Fig. 5 Results of cross-gender network comparison of the network of physical activity and sleep disturbances symptoms among college students. (**A**) results of the global strength invariance test; (**B**) results of the network structure invariance test

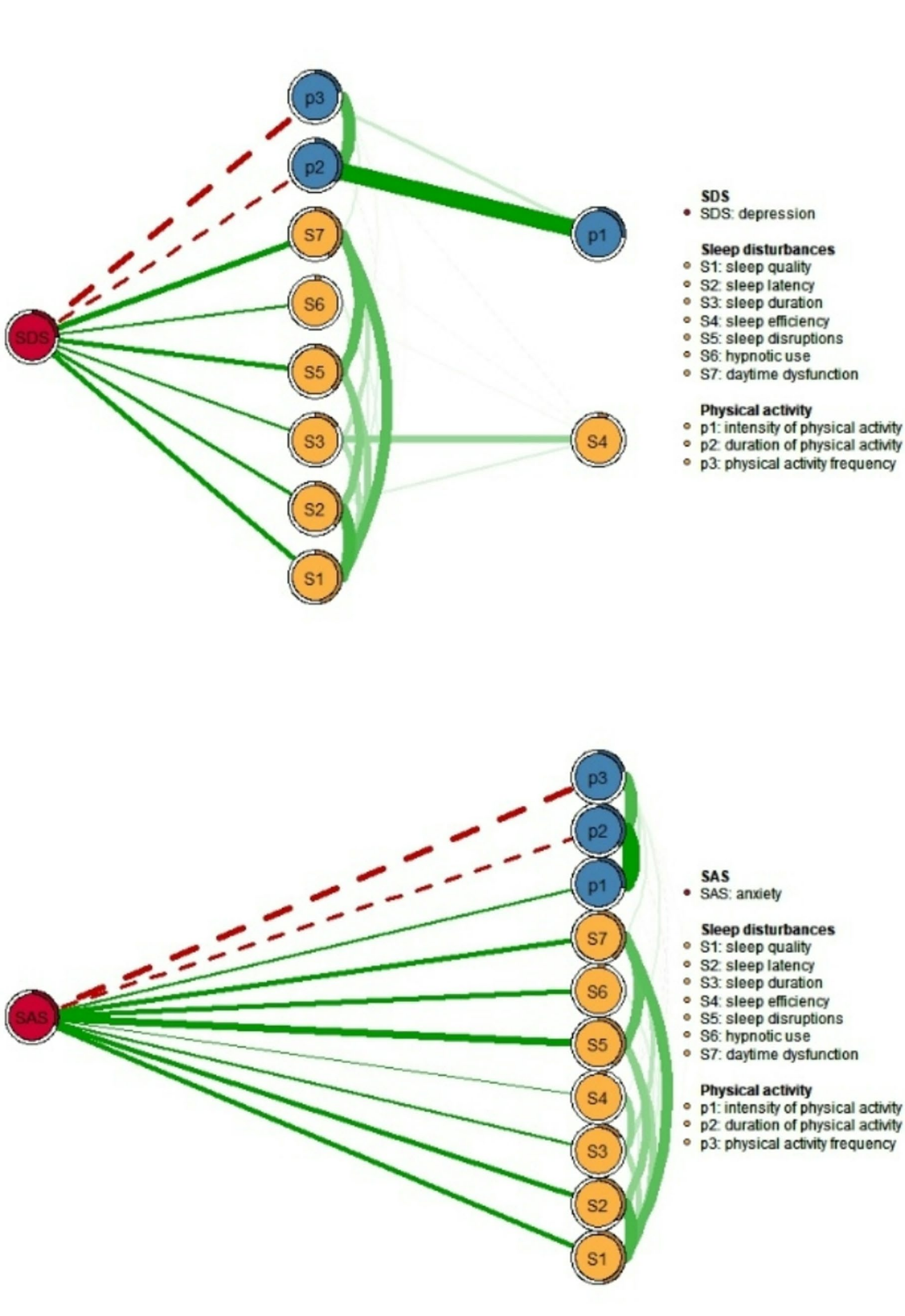

Fig. 6 Flow networks of depression and anxiety. (**A**) flow network of depression; (**B**) flow network of anxiety. Reveals symptoms directly correlated with anxiety and depression. Each node represents a symptom, and the lines between different nodes represent the correlation between nodes. The green solid line represents a positive correlation, and the red dashed line represents a negative correlation. The thicker the line, the stronger the correlation

the self-reinforcing nature of sleep disturbances. Our results align with Schlarb's study [61], which employed a multiple regression model to examine the relationship between sleep disturbances and somatization. The analysis revealed that while all dimensions of the Pittsburgh Sleep Quality Index significantly influenced sleep quality, sleep latency exerted the most substantial effect ($\beta = 0.26$). Furthermore, daytime dysfunction is relatively prevalent among college students. A survey indicated that 25.76% of college students exhibit high levels of daytime dysfunction [59]. Daytime dysfunction refers to the impairment of daytime cognition, emotions, and behavior caused by insufficient sleep or poor sleep quality, manifested as excessive drowsiness, fatigue, inattention, memory impairment, and mood swings, and is a core indicator of social functional impairment in sleep disturbance. In the symptom network of physical activity and sleep disturbances, daytime dysfunction emerged as the core symptom with the strongest correlation to sleep disruptions ($r = 0.319$). This indicates that more frequent sleep disruptions is associated with greater daytime functional impairment, aligning with previous research findings [61]. This phenomenon may be explained by the sleep disruptions exacerbates the accumulation of amyloid-β protein in the central nervous system [62], leading to structural and functional brain damage that subsequently worsens impairments in memory, executive function, and other cognitive domains [63].

Additionally, we discovered that "daytime dysfunction" and "intensity of physical activity" are key bridge symptoms in the symptom network of physical activity and sleep disturbance among college students. This indicates that the communication within the symptom network of physical activity and sleep disturbance is primarily mediated through daytime dysfunction and physical activity intensity. Within the sleep disturbances symptom clusters, daytime dysfunction serves as the bridge symptom with the strongest edge weight ($r = 0.035$) in its connection to physical activity frequency. However, we were surprised to find that there was a positive correlation between the two, meaning that the higher the score of daytime dysfunction, the higher the frequency of physical activity. This may be because our study population consists of college students, not clinical samples, and the sleep disturbances of the vast majority of participants does not meet clinical diagnostic criteria. Therefore, when individuals perceive daytime fatigue, drowsiness, and inattention, they may try to improve their state by increasing the frequency of physical activity. Secondly, within the physical activity symptom cluster, intensity of physical activity serves as the bridge symptom with the strongest edge weight ($r = -0.019$) in its connection to sleep latency.This may be because a higher level of physical activity intensity can promote energy consumption, leading to the breakdown of adenosine triphosphate into adenosine. As a homeostatic factor, the accumulation of adenosine enhances sleep drive and thereby shortens sleep latency [64]. However, previous studies have also indicated that excessive physical activity intensity can increase physiological arousal, activate the sympathetic nervous system, and elevate cortisol levels, thereby disrupting normal sleep cycles and leading to difficulties in sleep onset [65]. Therefore, further research is needed to explore the relationship between these two factors in greater depth.

Through network comparison, we found that there was no significant difference in global strength between the sleep quality and physical activity symptom networks of college students of different genders, but there were significant differences in network structure. The edge weight invariance test revealed significant differences in edge weights between the "intensity of physical activity" and "duration of physical activity" nodes in the networks of different genders (edge weight was 0.487 for males and 0.309 for females, $P<0.05$). This suggests that males are more inclined to engage in high-intensity and longer-duration exercise, a conclusion that has been validated in a review [66]. The reasons for this may be related to differences in hobbies and physiological levels between males and females. Males are inherently more physically energetic, enjoy competition and sports, and have higher muscle mass and a higher proportion of fast-twitch muscle fibers, which give them an advantage in explosive power and fatigue resistance. Furthermore, the testosterone hormone in males promotes muscle recovery, enabling them to maintain more sustained output [26].

Depression and anxiety are common mental health problems in college students. By constructing the flow network of depression and anxiety, we found that various factors of physical activity and sleep disturbances have direct and indirect negative effects on depression and anxiety, which supports Hypothesis 3. Among these factors, we found that "Physical activity frequency" exhibits strong negative correlations with both "anxiety" and "depression".This aligns with Denche et al.'s findings, which revealed that among populations with the highest physical activity frequency, the proportion of individuals without depressive symptoms peaked. Furthermore, the protective effect of exercise against depressive symptoms demonstrated a gradual strengthening trend as exercise frequency increased [67]. In this study, we also observed a strong positive correlation between daytime dysfunction and depression, aligning with Tashiro's findings [68]. This association may stem from impaired emotional regulation induced by daytime dysfunction [69]. Additionally, sleep disruptions demonstrated a significant positive association with anxiety. This finding is highly consistent with the research results of Ver. Ver conducted detailed monitoring of participants using actigraphy and found that individuals who experienced more sleep diaruptions often reported higher levels of anxiety, pain, and fatigue [70]. These research results provide support for improving the depressive and anxious states of college students.

The results of this study provide inspiration for university administrators. We found that in the network of physical activity and sleep disturbances symptoms, "daytime dysfunction" is both the core symptom and the bridge symptom of the network, and it has high predictability. Therefore, intervention in it can quickly and effectively improve low physical activity and sleep disturbances, and also reduce the information communication between physical activity and sleep disturbances. At the same time, we encourage a moderate increase in the duration of physical activity, as it has a negative correlation with all dimensions of sleep disturbances. Secondly, in the flow networks of depression and anxiety, we found that "physical activity frequency" has a strong negative correlation with both anxiety (r=−0.14) and depression (r=−0.14). Therefore, we advocate that university administrators provide students with a good sleep environment, regularly detect daytime dysfunction among college students, and offer courses on cognitive behavioral therapy and respiratory relaxation training to support the improvement of daytime dysfunction. In addition, we encourage college students to appropriately increase the duration and frequency of physical activities to improve their overall sleep quality and mental health.

Limitations and future direction

Although this study discussed the interrelationship between physical activity and sleep disturbances of college students from the perspective of symptoms, identified the core symptoms and bridge symptoms of the network, and used the flow network to discuss the impact of physical activity and sleep disturbances symptoms on depression and anxiety, providing a basis for the mental health intervention of college students, there are still certain limitations in this study: (1) This study used convenience sampling for the survey, which may affect the representativeness of the sample. Future research could adopt more rigorous sampling methods such as randomized stratified cluster sampling to provide stronger support for the study. (2) During the demographic information survey, this study did not include additional factors such as grade, family economic status, and parental conditions. These variables could be incorporated into analysis in future studies. (3) When constructing the networks for physical activity, sleep disturbances, depression, and anxiety, we did not consider the influence of other factors such as social support and interpersonal relationships on the results. Future research could control for these variables to further enhance result reliability. (4) As a cross-sectional study, this research cannot explore causal relationships between variables. Future studies could implement longitudinal networks to investigate causal relationships. (5) The sample of this study was drawn from three universities in Daqing City, resulting in certain geographical limitations. Caution may be needed when generalizing the results. Therefore, future research could include universities from more regions and conduct multi-center studies to improve result generalizability.

Conclusion

The correlation analysis method was used to investigate the relationship among physical activity, sleep disturbances, depression, and anxiety. The results showed that physical activity was negatively correlated with sleep disturbances, depression, and anxiety, while sleep disturbances were positively correlated with depression and anxiety. Further, we reveal the core and bridge symptoms in the physical activity and sleep disturbances symptom network through network analysis. "sleep quality" and "daytime dysfunction" were identified as the core symptoms, while "daytime dysfunction" and "intensity of physical activity" played the role of bridge symptoms. In the flow networks of depression and anxiety, we found that "physical activity frequency" and "daytime dysfunction" were particularly correlated with depression. Similarly, "sleep disruptions" and "physical activity frequency"showed a strong correlation with anxiety. These findings not only enhance our understanding of the complex relationship between physical activity, sleep disturbances, depression, and anxiety but also provide strong support for interventions to improve the health literacy of college students. Through targeted intervention for core symptoms and bridge symptoms, we are expected to improve the physical and mental health of college students more effectively.

Abbreviations

PARS	3 Physical activity scale-3
PSQI	Pittsburgh sleep quality index scale
SDS	Self-rating depression scale
SAS	Self-rating anxiety scale
GGM	Graphical gaussian model
LASSO	Least absolute shrinkage and selection operator
CS-C	Stability coefficient
NCT	Network comparison test
EI	Expected nfluence
BEI	Bridge expected influence

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Author contributions

JWY, WL: Conceptualization, Analysis, Writing - Original Draft, Methodology, Writing - Review & Editing. XJ, FY: Writing – original draft, Visualization, Software, Methodology, Formal analysis. ZJW: Writing review & editing, Writing – original draft, Supervision. JQC: Conceptualization, Methodology, Writing - Review & Editing, Funding acquisition.

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

Declarations

Ethics approval and consent to participate
This study was conducted in accordance with the declaration of Helsinki. the Ethics Committee of Harbin Medical University approved this study (HMUDQ20240711001). And to obtain the informed consent of the participants.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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