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The relationship between coauthorship and the research impact of medical doctoral students: A social capital perspective

Gang Chen[1,2,4], Wen-Wen Yan[2,4], Xi-Yu Wang[3], Qingshan Ni[2], Yang Xiang[1], Xuhu Mao[1] & Juan-Juan Yue[1]✉

Research impact is an important manifestation of research competence and the focus of medical education. This study is dedicated to exploring the relationships between coauthorship networks and the research impact of Chinese medical doctoral students from a social capital perspective. A total of 16291 scientific papers from 237 doctoral students and 126 mentors at Chinese universities were selected from databases, and a study dataset including 19 variables was constructed. Nine independent variables were defined and obtained through coauthorship network analysis, and the doctoral students' research impact, as the only dependent variable, was used to test the hypothesized relationships among the variables. The results show that the *betweenness centrality*, *student-mentor coauthorship count* and the *partnership ability index* significantly affect the *h-index*. Specifically, the *coauthorship unit count* plays the most important role in developing centrality, which, in turn, produces a higher *h-index*. In addition, *betweenness centrality*, *student–mentor coauthorship count* and the *partnership ability index* are good predictors of the likelihood of doctoral students entering the greater research impact group and especially improving their *betweenness centrality*. Specifically, doctoral students whose *partnership ability index* is greater than 2, *student-mentor coauthorship count* is greater than 4, *coauthorship unit count* is greater than 6, and *betweenness centrality* is greater than 0.02 are considered to have greater research impact. These findings suggest that the important roles of cooperation in the development of research competence and good mentorship in the acquisition of social capital by doctoral students should be emphasized. Several strategies are advised for harnessing social capital rooted in doctoral students' coauthorship network for relevant organizations, mentors and doctoral students who want to increase medical doctoral students' research impact.

[1] Department of Clinical Microbiology and Immunology, Faculty of Pharmacy and Medical Laboratory Sciences, Army Medical University (Third Military Medical University), Chongqing, China. [2] Biomedical Analysis Center, College of Basic Medicine, Army Medical University (Third Military Medical University), Chongqing, China. [3] School of Foreign Languages, University of Jinan, Jinan, Shandong, China. [4] These authors contributed equally: Gang Chen, Wen-Wen Yan. ✉email: yuejuanjuan@tmmu.edu.cn

Introduction

Research competence is regarded as the core competence of medical practitioners to meet growing global health care needs, and the educational community has called for medical students to develop and acquire research skills and attributes as early as possible (Laidlaw et al. 2012). Publications in journals are seen as important outcomes of scientific research. Universities in many countries, including China, have adopted a policy in which publications are required for medical doctoral students to obtain their degrees (Cargill et al. 2018; Corsini et al. 2022). This has led to China's rapid ascent to second place globally in the number of Science Citation Index (SCI) articles, and it may also affect the quality of publications to some extent (Zhu et al. 2014). The research impact of publications represents the intellectual contribution in the academic field, which is seen as an indicator to evaluate the intrinsic quality of the research (Penfield et al. 2014). Therefore, it is very important to enhance the research impact of doctoral students to promote the development of medical education.

Social capital theory (SCT) has been widely applied to improve the relationships among educational groups, thereby enhancing learning outcomes and teaching effectiveness (Keung and Cheung, 2023). Social capital is often defined as all potential resources rooted in social networks formed by interpersonal interactions (Adler and Kwon, 2002). It includes three dimensions: structural capital, cognitive capital, and relational capital (Claridge, 2018). Structural capital describes the patterns of connections among people or units in social network structures (Li et al. 2013). Cognitive capital generally refers to individuals' knowledge, skills, professional discourse, and practical learning norms from interactions with others within a collective (Wasko and Faraj, 2005). Relational capital, which focuses on how people's special relationships, such as respect and friendship, affect their behavior, is the capital created and leveraged through interpersonal relationships (Nahapiet and Ghoshal, 1998). Scientific cooperation can bring abundant resources, a reasonable social division of labor and channels for knowledge diffusion, which has been proven to be conducive to increasing research productivity (Abramo et al. 2017; Yue et al. 2019). Coauthorship represents an important form of cooperation, which occurs when researchers collaborate and publish an article together (Kumar, 2015), and multiple coauthorship relationships are combined to construct the coauthorship network. Coauthorship networks are valuable social networks, and social capital from these networks has been proven to have a positive effect on research impact (Li et al. 2013; Xu and Chang, 2020).

As most doctoral students are novices in academia, they do not have the ability to independently publish papers with others to establish a coauthorship relationship at the beginning of their studies, mentorship is adopted in medical graduate education to help them develop their abilities (Witry et al. 2013). Mentors provide students with research and teaching guidance to help them develop their skills and expand their influence in the professional world, provide them with emotional and psychological support, and motivate them to overcome difficulties and move forward toward their goals (Carey and Weissman, 2010). These interactions help doctoral students develop their cognitive capital. The more professional knowledge and skills a mentor possesses, the greater the likelihood is that he or she will contribute cognitive capital to his or her doctoral students (Wasko and Faraj, 2005). As cognitive capital also includes mastering the application of expertise, mentors with more experience may better understand the relevance of their expertise and have cumulative advantages that enable them to provide their doctoral students with more helpful guidance (Malmgren et al. 2010; Wasko and Faraj, 2005).

However, the volume of this flow of social capital from mentors to doctoral students can vary greatly, and creating a more satisfactory relationship may promote the transfer of capital (Ahmad et al. 2023). When doctoral students are coauthors with their mentors, these relationships are good demonstrations of mutual trust, commitment and reciprocity (Moorman et al. 1993). Relational capital exists under these conditions and plays a role in providing more resources to doctoral students. For example, more collaborators provide new knowledge and perspectives to generate creativity (Perretti and Negro, 2006), and diverse cooperative teams provide their own specific expertise, enabling students to overcome their individual cognitive limitations and generate new ideas (Oh et al. 2005) and maintain stable cooperative relationships with others to share resources and maximize cooperative benefits (Li et al. 2013).

As doctoral students mature and gradually establish their individual coauthorship networks, their position in these networks brings structural capital. Centrality, an important structural attribute, is often used to represent the formal power or prominence of a target in a network relative to others, including *closeness centrality*, *betweenness centrality* and *degree centrality* (Kumar, 2015). *Degree centrality* is defined as the number of direct connections between the target doctoral student and his or her coauthors regardless of connection strength, *closeness centrality* is defined as the mean shortest distance from the target doctoral student to all other coauthors, and *betweenness centrality* is defined as the proportion of the shortest paths between all pairs of nodes that pass through the target doctoral student (Borgatti, 2005). Doctoral students with high centrality in coauthorship networks are likely to have access to more resources to enhance their research impact.

Previous studies have confirmed that a good relationship between a mentor and mentee is more helpful for realizing the objectives of mentorship (Straus et al. 2013; Straus et al. 2009; Yu et al. 2022). However, these studies mainly make recommendations on the basis of feedback from interviews and questionnaires, and few studies have used coauthorship network analysis to further mentorship development in the medical field. The purpose of this study is to explore the relationship between coauthorship and the research impact of doctoral students from a social capital perspective. This study attempts to answer the following three questions: 1) What social capital from the coauthorship network affects the research impact of doctoral students? 2) What is the path through which these types of social capital affect the research impact? 3) What special effect pattern does this social capital have on doctoral students' research impact? The findings of this study can identify different types of social capital presented in coauthorship that might contribute to doctoral students' research impact and help us better understand and implement mentorship in medicine.

Methodology

Samples. A total of 250 medical doctoral students who graduated from 2016 to 2021 from two major medical universities, Army Medical University and Chongqing Medical University, in Chongqing, China, and their mentors were selected as the research objects. This represented 14.5% of all the doctoral students who graduated from the two universities during this period. We chose these universities for the following reasons: (1) They have consistently performed well in scientific research among Chinese medical universities. (2) Both universities are located in Chongqing, and they have a long history of extensive cooperation in postgraduate training and scientific research, which enables us to explore their coauthorship networks and collaboration. (3) We

could easily verify and refine the author's information from the two universities through interpersonal relationships to ensure the accuracy of the data as much as possible. (4) Both universities require doctoral students to publish academic works with certain impact factors in foreign journals included in the SCI before earning a degree. (5) All the graduate papers from the two universities can be retrieved from the Chinese National Knowledge Infrastructure (CNKI) database. We sampled doctoral graduates according to their disciplines, including clinical medicine and basic medicine. There were 125 samples from each university. We used the following exclusion criteria to filter the raw sample and obtain the effective sample: (1) Doctoral students who had not published SCI papers during their studies; (2) Incomplete data or extensive missing data; (3) Cases in which it could not be determined whether the data were related to the research object. Ultimately, 237 valid samples were obtained, including 117 from Army Medical University and 120 from Chongqing Medical University.

Data collection and preprocessing. All the data for this study were gathered from the CNKI database and Web of Science (WoS) database. The CNKI is the largest Chinese academic literature database, with a complete collection and continuously updated graduate dissertations and related information (Zuo et al. 2021), and the WoS contains publications in almost all major scientific fields and is considered an ideal database for literature research (Zuo et al. 2021).

The specific process of data collection was as follows: We obtained the doctoral student's name, department, major, doctoral study periods and mentor information from the CNKI database. Then, we obtained the publications and *h-index* of the samples through the WoS. Publications were retrieved from the WoS through a set of developed search terms, and the time span was set for doctoral students as their training period and for mentors as the mentors' tenure. Publications, which encompassed all papers in which the target appeared in any position in the authorship, included articles, reviews, meeting abstracts, and short essays. For each publication, we extracted the title, publication date, coauthors and addresses. The data collection from the CNKI database was completed in May 2022, and the publication collection was completed in December 2022. The raw data consisted of 21686 publications by 250 doctoral students and their mentors.

The preprocessing of publication data is key to obtaining reliable analysis results. In this study, the original data were processed as follows: (1) Publications were checked manually by author names, units and research areas to disambiguate authors with the same name (Zeng et al. 2017). First, we checked whether the author's byline name was the same. For example, the results of a search for papers by Li Xuliang, an author from Chongqing Medical University showed that Li Xuliang, Li Xu Liang, Li, Xuliang, Li Xu-liang and Li, Xianliang might or might not be the same author. Then, we further checked whether the above authors were from Chongqing Medical University, and papers not from this school were excluded. Finally, we checked whether the research topics of the remaining papers were in line with the target author's major and research field from the CNKI database. If not, the authors were judged not to be the target author. If the author's name in the article was abbreviated in the WoS, it was reverified with the DOI (digital object identifier), title and other information through other databases, such as PubMed and Sci-Hub, and if it was still not confirmed, it was deleted. (2) One researcher labeled the papers of nonsubjects and eliminated the duplicate papers under one author, and another researcher crosschecked the data until the two reached a consensus. (3) We then manually standardized the writing formats of each author's name in all publications. Ultimately, 5395 papers were excluded, and the remaining 16291 papers, by 237 doctoral students and 126 mentors, were retained. Among them, 1441 papers were published by authors who were then doctoral students. We linked all the information retrieved from the above database with the student-mentor pairs in a new dataset so that we obtained a research sample consisting of 237 such pairs (see Dataset 1).

Variables

Dependent variable. We used the *h-index* of the doctoral students' published papers as the only dependent variable. The well-known *h-index*, proposed by Hirsch in 2005 (Hirsch, 2005), is used to evaluate an individual's research impact objectively (Wendl, 2007). This index is calculated on the basis of publications and citations (Abbas, 2012) as follows: $h=\max(i):C_i \geq i$. (Suppose the papers are arranged in descending order of the number of citations, and let C_i be the number of citations of a paper numbered i.). The *h-index* in this study was obtained through the WoS database on the basis of published papers and citations.

Independent variables. We constructed nine variables from cognitive capital, structural capital and relational capital in doctoral students' coauthorship networks.

1. Cognitive capital included *mentors' h-index* and *fecundity*, which are common measures of mentors' academic success (Ma et al. 2020; Malmgren et al. 2010). *Fecundity* was defined as the number of postgraduates supervised by the mentor from the enrollment year of the first postgraduate supervised by the mentor to the graduation year of the target doctoral student, excluding the target doctoral student.
2. Structural capital was evaluated by doctoral students' *closeness centrality*, *betweenness centrality* and *degree centrality* (Kumar, 2015). The centralities were calculated via UCINET software (Borgatti et al. 2002) based on the coauthorship networks, which were constructed via Co-Occurrence (COOC) software (Qin et al. 2022).
3. Relational capital was measured by the *doctoral students' coauthor count*, *coauthorship unit count*, *student-mentor coauthorship count* and the *partnership ability index* (Schubert, 2012). The *doctoral students' coauthor count* and *doctoral students' coauthorship unit count* were obtained by manual calculation on the basis of the students' publications, and the duplicate coauthors and coauthor units were calculated only once. The *student-mentor coauthorship count* was the number of publications in which the student appeared with his or her mentor in the coauthorship of a publication. The *partnership ability index*, proposed by Schubert to assess authors' cooperation behaviors, comprehensively reflects the number of collaborators and number of repeats of cooperation (Schubert, 2012). Its calculation method is shown in Fig. S1 (see the Supplementary file).

Control variables. The characteristics of the doctoral students and mentors were used as control variables, such as the *doctoral students' subject*, *doctoral students' training period*, *mentors' title* and *mentors' tenure*. The *doctoral students' subject* and *training period* were controlled for heterogeneity across the thesis research fields and for research time effects. The title and tenure of the mentor were controlled for his or her experience and time influence in research and mentoring activities. These variables were not relevant to the study's aims but were controlled because

Table 1 List of variables used in the analysis.

Variables	Description	Source
Dependent variable		
Doctoral students' h-index	The h-index was calculated according to the number and citations of publications between Y_g and Y_e[a].	WoS database
Independent variables		
Cognitive capital		
Mentors' h-index	The h-index was calculated according to the number and citations of publications between Y_g and Y_f.	WoS database
Mentors' fecundity	The number of all postgraduate students supervised by the mentor from Y_f to Y_g minus 1.	Data accumulation through CNKI database
Structural capital		
Degree centrality	The number of direct connections between the target doctoral student and other coauthors regardless of the connection strength in the coauthorship network.	UCINET software
Closeness centrality	The mean shortest distance from the target doctoral student to all the other coauthors in the coauthorship network.	UCINET software
Betweenness centrality	The proportion of the shortest paths between all the pairs of nodes that pass through the target doctoral student in the coauthorship network.	UCINET software
Relational capital		
Doctoral students' coauthor count	The number of coauthors in the doctoral student's publications excluding herself or himself, and the count is still 1 if the same coauthor appears more than once in the publications.	Data calculation based on publications analysis
Doctoral students' coauthorship unit count	The number of coauthorship units in the doctoral student's publications excluding her or his own unit, and the count is still 1 if the same unit appears more than once in the publications.	Data calculation based on publications analysis
Student-mentor coauthorship count	The number of publications in which the student coappeared with his or her mentor in the coauthorship of a publication.	Data calculation based on publications analysis
Doctoral students' partnership ability index	The collaborators of a certain author are listed in descending order by the frequency of their cooperation with the author. When the author serial number is greater than the corresponding cooperation frequency for the first time, the serial number minus 1 is the author's partnership ability index.	Data calculation based on publications analysis
Control variables		
Doctoral students' subject	Dummy variables that equal one if the doctoral student's subjects are in clinical medicine.	CNKI database
Doctoral students' training period	The number of years elapsed from Y_e to Y_g.	Calculation by data from CNKI database
Mentors' title	A dummy variable that equals one if the mentor is a professor.	CNKI database
Mentors' tenure	The number of years elapsed from Y_f to Y_g.	Calculation by data from CNKI database

Note: Y_e is the target doctoral student's enrollment year; Y_g is the target doctoral student's graduation year; Y_f is the enrollment year of the first postgraduate supervised by the mentor.

they might have influenced the outcomes (Corsini et al. 2022). All the variables included in our analysis are listed in Table 1 with a short description and sources.

Hypotheses. A predesigned model (see Fig. 1) on the basis of SCT was proposed to facilitate answering the first two questions, that is, what social capital from coauthorship networks influences the research impact of doctoral students and its action paths? To examine the influence of cognitive capital on research impact, we predicted that doctoral students who are supervised by more academically successful mentors will have greater research impact (H1a, H1b), that is:

H1a: A higher *mentor' s h-index* is associated with a higher *doctoral students' h-index*.

H1b: Higher *mentor' s fecundity* is associated with a higher *doctoral students' h-index*.

We further hypothesized that doctoral students with greater centrality in their coauthorship networks will have greater research impact (H2a, H2b, H2c), as follows:

H2a: Higher *doctoral students' closeness centrality* is associated with a higher *h-index*.

H2b: Higher *doctoral students' betweenness centrality* is associated with a higher *h-index*.

H2c: Higher *doctoral students' degree centrality* is associated with a higher *h-index*.

Building on the previous hypotheses, H2a, H2b and H2c sought to verify the relationship between structural capital and research impact, and the effects of relational capital on this relationship were also tested by the following hypothesis. Doctoral students who have established good cooperative relationships with others (units) will have greater research impact (H3a, H3b, H3c, H3d). Therefore, we postulated the following:

H3a: A higher *doctoral students' coauthor count* is associated with a higher *h-index*.

H3b: A higher *doctoral students' coauthorship unit count* is associated with a higher *h-index*.

H3c: A higher *doctoral students' student-mentor coauthorship count* is associated with a higher *h-index*.

H3d: A higher *doctoral students' partnership ability index* is associated with a higher *h-index*.

Moreover, the associations among the three dimensions of social capital and among the three centralities of structural capital were used to refine the model. Doctoral students with insufficient structural capital in the early stages of their studies are likely to expand their social networks by investing in their relational and cognitive capital through cognitive efforts and proactive behaviors (Li et al. 2013; Smith, 2007). Mentors with a high *h-index*

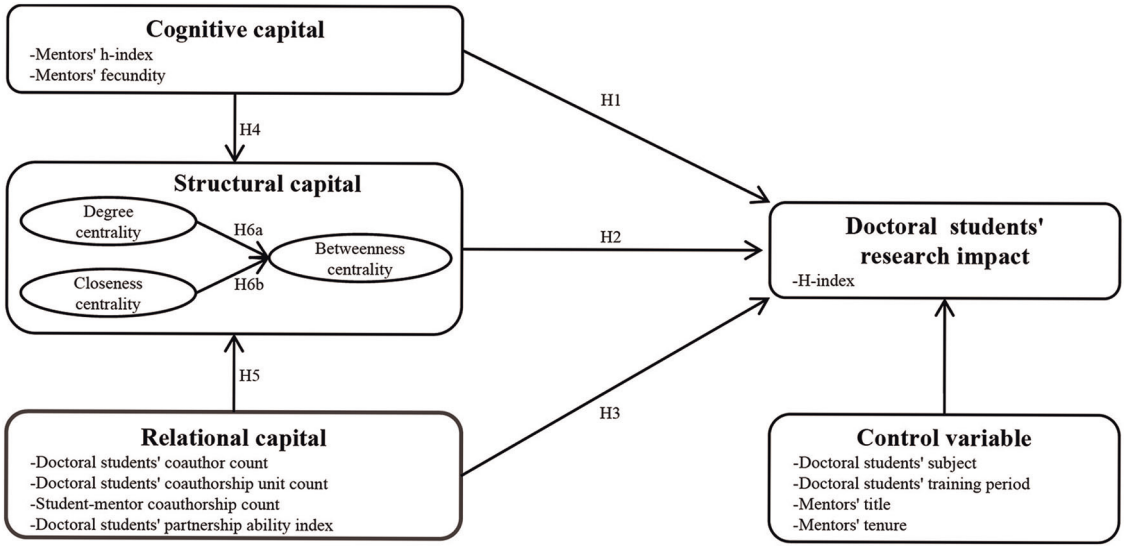


Fig. 1 Conceptual framework.

may work with more collaborators, which, in turn, may bring more close collaborators to students (McCarty et al. 2013). Thus, we predicted that doctoral students supervised by mentors with a higher *h-index* will have more structural capital and will especially improve their *closeness centrality* and *degree centrality* (H4a, H4b). The specific hypotheses were as follows:

H4a: A higher *mentors' h-index* is associated with higher *doctoral students' closeness centrality*.

H4b: A higher *mentors' h-index* is associated with higher *doctoral students' degree centrality*.

Similarly, we hypothesized that doctoral students with more relational capital will bring in more structural capital (H5a, H5b, H5c, and H5d), and H5a covers the three assumptions about the effects of one indicator of relationship capital on *closeness centrality, betweenness centrality* and *degree centrality*, as do H5b, H5c and H5d. Thus, the following hypotheses were proposed:

H5a (1,2,3): A higher *doctoral students' coauthor count* is associated with higher *closeness centrality/betweenness centrality/degree centrality*.

H5b (1,2,3): A higher *doctoral students' coauthorship unit count* is associated with higher *closeness centrality/betweenness centrality/degree centrality*.

H5c (1,2,3): A higher *doctoral students' student-mentor coauthorship count* is associated with higher *closeness centrality/betweenness centrality/degree centrality*.

H5d (1,2,3): A higher *doctoral students' partnership ability index* is associated with higher *closeness centrality/betweenness centrality/degree centrality*.

Additionally, an actor should first establish direct contact and then develop close relationships with her or his collaborators so that she or he can become the key controller of effective communication in the network. Therefore, we predict that the higher the *degree centrality* or *closeness centrality* is, the greater the actor's *betweenness centrality* is likely to be (H6a, H6b).

H6a: Higher *doctoral students' degree centrality* is associated with higher *betweenness centrality*.

H6b: Higher *doctoral students' closeness centrality* is associated with higher *betweenness centrality*.

Measurement. In this study, Co-Occurrence12.8 (COOC) software was used to construct and analyze the co-occurrence matrix. COOC software is bibliometric software that uses accurate character segment recognition algorithms to ensure the quality of data analysis (Qin et al. 2022). The author list from each student's papers was input into the software to construct a co-occurrence matrix, with each number in the matrix indicating the number of times any two people were coauthors, which was the basis for calculating the *doctoral students' coauthor count*, the *partnership ability index* and the *student-mentor coauthorship count*. Additionally, the co-occurrence matrix is the data form analyzed by UCINET software, which is a common tool for social network analysis that can compute the centralities for each node in a matrix (Borgatti et al. 2002). All the authors listed in the papers from 237 doctoral students were imported into the COOC software, from which 4380 coauthors were extracted to construct a co-occurrence matrix (4380×4380), which was then imported into the UCINET software to calculate the *closeness centrality*, *betweenness centrality* and *degree centrality* of the doctoral students. The software operation process is shown in the Supplementary File.

Finally, the data were analyzed using SPSSAU online application software (version 23.0), which was retrieved from https://www.spssau.com. Nonparametric tests were selected because of the nonnormal distribution of the data. Descriptive statistics, Spearman correlation analysis and path analysis were used to answer the first two research questions: what social capital affects the research impact of doctoral students, and what is the action path of this effect? Descriptive statistics and Spearman correlation analysis were used to analyze the basic characteristics of the relationships among all the indicators. Path analysis in structural equation modeling (SEM) was adopted to test the hypothesized associations and the predesigned model (see Fig. 1), which can simultaneously evaluate relationships among multiple variables and provide model fitting data to verify the degree of match between the predesigned model and the empirical data (Davvetas et al. 2020). Quantile regression, logistic regression and receiver operating characteristic (ROC) curves were further used to answer the last research question: what is the special effect pattern of this social capital on the research impact of doctoral students? We focused on the influencing trends and predictive effects among the variables, which are valuable for improving the doctoral students' learning process. Quantile regression was performed to explore the influence of independent variables on the *h-index* when the dependent variables were divided into 9 parts at a 10% interval (Das et al. 2019). Subsequently, the doctoral students at the top and bottom 30% of the *h-index* were divided into an excellent group and a poor group. The Wilcoxon

rank-sum test was used to test differences in the indicators between the groups. Logistic regression was used to identify the independent variables that could predict the probability of a doctoral student entering the excellent group. The single-variable ROC curves were chosen instead of the comprehensive multi-variable ROC curve because they could further evaluate the predictive efficacy of each independent variable on the students' *h-index* and determine its optimal cutoff value, which provides a specific standard reference in practice (Søreide et al. 2011). Finally, a robustness check was used to ensure the reliability of the results, and two-tailed $p < 0.05$ was considered statistically significant.

Results

Descriptive statistics, correlation analysis, path analysis and quantile regression analysis were first performed on the total sample ($n = 237$). The logistic analysis and ROC curve analysis were then performed on the subsample ($n = 175$). Finally, a robustness check was used to explore the stability of the results across the whole sample ($n = 237$).

Descriptive statistics. The sample consisted of 237 doctoral students, 79% of whom were clinical medicine students ($n = 188$); the rest were basic medicine students. The mean doctoral training time of the students was 3.6 years (SD = 0.99). They had published an average of 6.1 papers during their training, with the publication years ranging from 2012–2021. The mentors were almost all professors, with an average tenure of 15.8 years (SD = 4.71), an average of 62.7 publications, and the highest *h-index* of 38 (see Table 2). The *h-index* of the doctoral students had a positive relationship with all the independent variables ($r_s = 0.26 \sim 0.80$, $p < 0.01$) except *mentors' fecundity* (see Table S1).

Table 2 Descriptive statistics for the 237 doctoral student-mentor pairs.

Variables	Mean (SD)/no. (%)	Min	Max
Doctoral students' h-index	4.17 (2.96)	0.00	17.00
Doctoral students' publications	6.08 (4.46)	1.00	22.00
Doctoral students' yearly citation count	16.37 (17.93)	0.00	128.78
Mentors' h-index	18.41 (7.28)	0.00	38.00
Mentors' publications	62.66 (39.96)	1.00	202.00
Mentors' yearly citation count	119.13 (109.76)	0.00	731.10
Mentors' fecundity	44.87 (29.58)	1.00	113.00
Degree centrality	0.64 (0.49)	0.02	3.56
Closeness centrality	1.00 (0.18)	0.02	1.04
Betweenness centrality	0.22 (0.46)	0.00	4.38
Doctoral students' coauthor count	16.50 (17.22)	1.00	123.00
Doctoral students' coauthorship unit count	6.86 (6.26)	0.00	43.00
Student-mentor coauthorship count	4.64 (3.91)	0.00	18.00
Doctoral students' partnership ability index	3.15 (1.81)	0.00	10.00
Doctoral students' training period	3.64 (0.99)	3.00	10.00
Mentors' tenure	15.80 (4.71)	3.00	25.00
Doctoral students' subject		0.00	1.00
Clinical medicine	188 (79.3%)		
Basic medicine	49 (20.7%)		
Doctoral students' university			
Army Medical University	117 (49.4%)		
Chongqing Medical University	120 (50.6%)		
Mentors' title		0.00	1.00
Professor	233 (98.3%)		
Associate professor	4 (1.7%)		

Path analysis. The path analysis results (see Fig. 2) revealed that *betweenness centrality* (H2b: $\beta = 0.29$, $p < 0.001$), *the partnership ability index* (H3d: $\beta = 0.38$, $p < 0.001$), and the *student-mentor coauthorship count* (H3c: $\beta = 0.33$, $p < 0.001$) had a significant impact on the *doctoral students' h-index*. The values of the variance inflation factor (VIF) of the variables were less than 5 except for *degree centrality* (VIF = 7.23), which was below the common threshold of 10.0, indicating that multicollinearity among these variables was acceptable (see Table S1). This finding supported the important hypothesis that the structural capital and relational capital of doctoral students positively affect their *h-index*. The results regarding the influence of cognitive capital and relational capital on structural capital revealed that *mentors' h-index*, *doctoral students' coauthor count*, *coauthorship unit count*, the *partnership ability index* and *student-mentor coauthorship count* all had significant effects on the three centralities of structural capital. Moreover, *degree centrality* had a significant positive effect on *betweenness centrality* (H6a: $\beta = 1.01$, $p < 0.001$), and *closeness centrality* did not have this effect. In addition, *mentors' tenure*, as a control variable, had a significant effect on *doctoral students' h-index* ($\beta = -0.14$, $p < 0.01$). The independent variables explained 72% of the *h-index*, 76% of the *betweenness centrality*, 9% of the *closeness centrality* and 64% of the *degree centrality*. Therefore, nine hypotheses proposed in this study were accepted, and the others were rejected (see Table 3).

We assessed the goodness of fit of the model via several commonly used measures: the chi-square degree of freedom ratio (χ^2/df), the comparative fit index (CFI), the standardized root mean square residual (SRMR), the root mean square error of approximation (RMSEA), and the nonnormed fit index (NNFI) (Hooper et al. 2008; McDonald and Ho, 2002). The widely used empirical rules state that the model fit is excellent when the value of χ^2/df is less than 3 (χ^2/df=1.12, $p > 0.05$), the CFI and NNFI exceed 0.95, the SRMR is less than 0.05 (SRMR = 0.02) and the RMSEA is less than 0.05 (RMSEA = 0.02) (Hooper et al. 2008; Keinänen et al. 2018).

Quantile regression analysis. In the quantile regression analysis, we focused on the four variables that had a direct significant effect on the *h-index* in the path analysis: *betweenness centrality*, *student-mentor coauthorship count*, the *partnership ability index* and *mentors' tenure*. The results revealed different influence trends of these variables (see Fig. 3). The strength of *betweenness centrality* increased incrementally on the *h-index* from 0.15 (B: $\beta = 1.25$, $p < 0.001$) to 0.65 (B: $\beta = 2.81$, $p < 0.001$), then decreased to 0.75 (B: $\beta = 2.40$, $p < 0.001$) and finally began to increase rapidly to 0.95 (B: $\beta = 3.82$, $p < 0.001$). The significant effect of the *student-mentor coauthorship count* on the *h-index* increased incrementally from quantiles 0.05 (A: $\beta = -0.14$, $p < 0.001$) to 0.85 (A: $\beta = 0.40$, $p < 0.001$) and then decreased to quantiles 0.95 (A: $\beta = 0.31$, $p < 0.05$). The effect of *the partnership ability index* on the *h-index* fluctuated before the 0.55 quantile, and the effect gradually increased from the 0.55 quantile (B: $\beta = 0.50$, $p < 0.001$), especially from the 0.85 quantile (B: $\beta = 0.74$, $p < 0.001$) to the 0.95 quantile (B: $\beta = 1.13$, $p < 0.001$). *Mentors' tenure* had a significant negative effect only on the *h-index* at the 0.95 quantile (B: $\beta = -0.05$, $p < 0.05$) and had no effect on the other quantiles.

Logistic regression and ROC curve analysis. The subsample consisted of 175 doctoral students and was divided into an excellent group (n = 88) and a poor group (n = 87). Wilcoxon rank-sum tests were conducted to compare the numbers of publications and

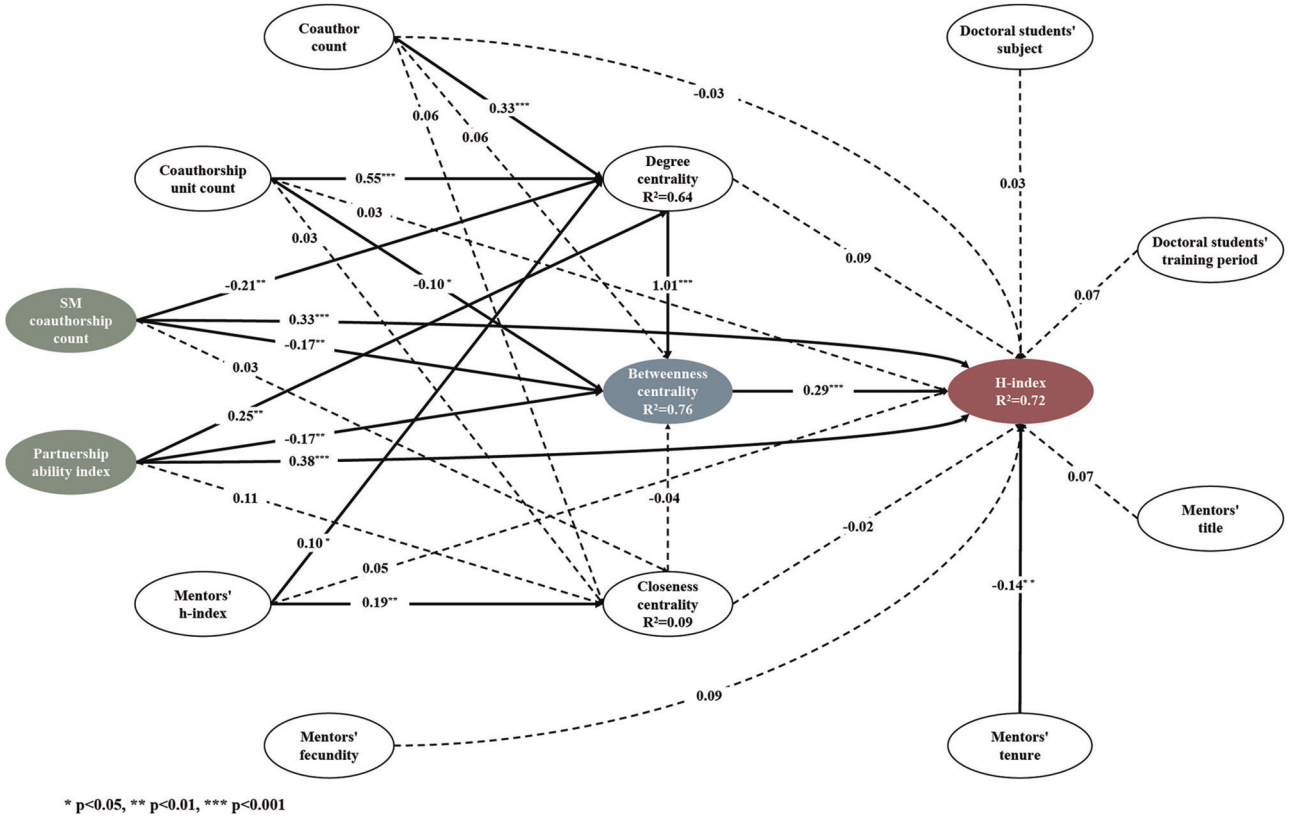


Fig. 2 Structural equation modeling (SEM) of the relationships between the variables. The coauthor count represents doctoral students' coauthor count; the coauthorship unit count represents doctoral students' coauthorship unit count; the SM coauthorship count represents the student-mentor coauthorship count; and the partnership ability index represents doctoral students' partnership ability index.

yearly citation counts between the two groups, revealing significant differences ($p < 0.001$), but there was no significant difference in the *doctoral students' training period* (Fig. 4c). The three variables of *betweenness centrality*, *student-mentor coauthorship count* and the *partnership ability index* were included in the subsequent analysis, while *mentors' tenure* had only a weak negative effect on the *h-index* for specific doctoral students in the quantile regression; thus, it was excluded from the variables. The logistic regression model was statistically significant ($\chi^2 = 194.47$, $df = 3$, $p < 0.001$) and explained 80% of the reasons for students entering different groups. The independent variables of *student-mentor coauthorship count* ($z = 2.65$, $p < 0.01$), the *partnership ability index* ($z = 3.17$, $p < 0.01$) and *betweenness centrality* ($z = 3.82$, $p < 0.001$) had significant predictive effects on the *h-index*. By coauthoring publications with their mentors, doctoral students increased the likelihood of their *h-index* being in the top 30% by 87.6% (OR 1.88, 95% CI 1.18 ~ 2.99). For each one-unit increase in the *partnership ability index* (OR 7.73, 95% CI 2.19 ~ 27.32) and *betweenness centrality* (OR 2476.18, 95% CI 44.97 ~ 136339.17), doctoral students were nearly 8-fold and more than 2000-fold more likely to enter the excellent group, respectively. The overall prediction accuracy of the model was 94.29%, and the Hosmer–Lemeshow test ($p > 0.05$) revealed that the model fit was acceptable. The formula of the model is expressed as follows:

$$\ln\left(\frac{p}{1-p}\right) = -9.91 + 0.63 \times \text{SMcoauthored} + 2.05 \times \text{Partnership} + 7.81 \times \textit{B}\text{etweenness centrality}$$

Note: p represents the probability of being in the excellent group, SMcoauthored represents the *student-mentor coauthorship count*, and Partnership represents the *partnership ability index*.

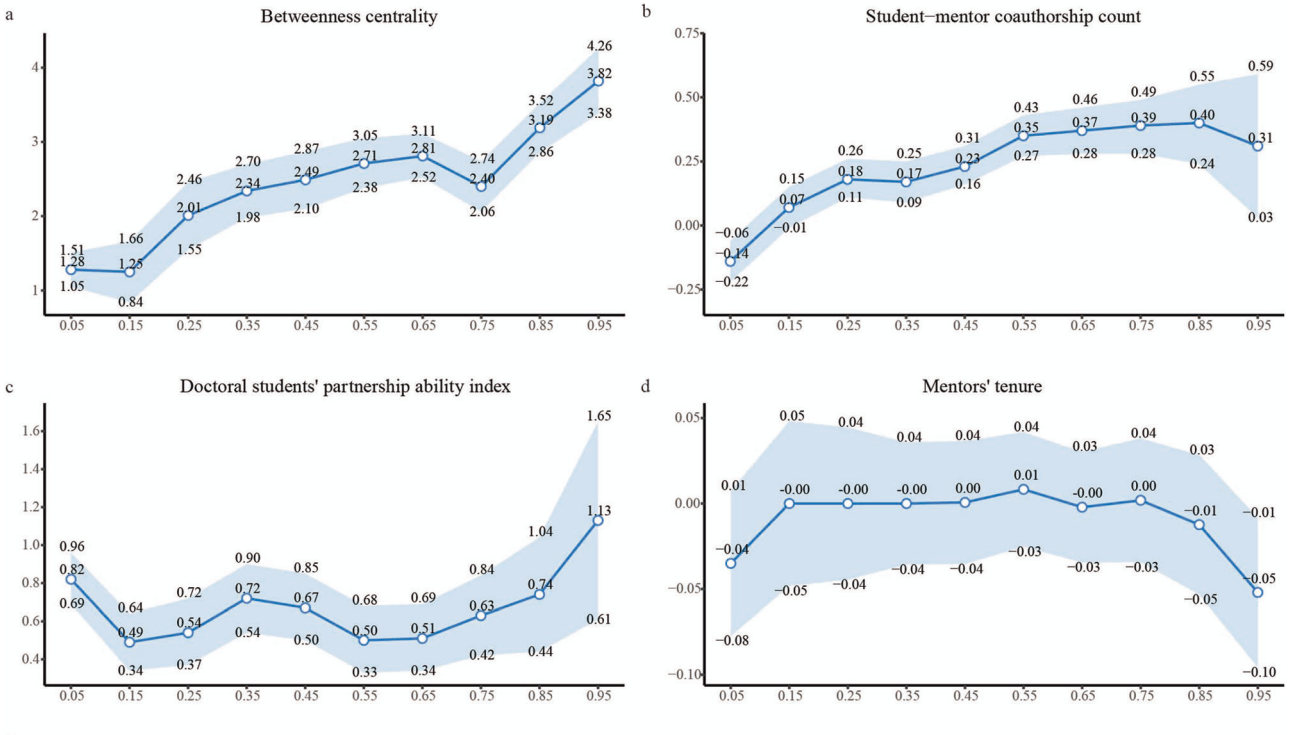
ROC curve analysis was performed on the important predictors of the above results, including *betweenness centrality*, *student-mentor coauthorship count* and *the partnership ability index*. However, since *betweenness centrality* could only be obtained through social network analysis software, it would be difficult to formulate improvement measures for management. Therefore, *doctoral students' coauthorship unit count*, which had a significant effect on *betweenness centrality* in path analysis, was also included in the analysis. The area under the ROC curve (AUC) values of the *student-mentor coauthorship count*, *partnership ability index*, *betweenness centrality* and *coauthorship unit count* were 0.92 (95% CI 0.87 ~ 0.96, $p < 0.001$), 0.96 (95% CI 0.93 ~ 0.98, $p < 0.001$), 0.86 (95% CI 0.80 ~ 0.91, $p < 0.001$), and 0.88 (95% CI 0.84 ~ 0.93, $p < 0.001$), respectively. The Youden index values were 0.77, 0.77, 0.62 and 0.60, respectively. The results revealed that the *student-mentor coauthorship count* and the *partnership ability index* were highly valuable in predicting whether doctoral students would enter the excellent group, with optimal cutoff values of 4 and 2, respectively. The *betweenness centrality* and *coauthorship unit count* also had certain values, with optimal cutoff values of 0.02 and 6, respectively (see Fig. 5).

Robustness check. To make the results more likely to reflect the current situation, we chose doctoral students who had graduated in recent years as the samples. We considered the time lag effect of citations after publication because article citations may be low during the first few years after publication. Although a reasonable citation time window is still under debate, some studies suggest that citations reach a maximum at two years after an article is published (Schreiber, 2015). However, of all the

Table 3 Hypothesis testing.

Hypothesis	Relationship			UnStd.	S.E.	C.R.	*p*	Std.(β)	Results
H2b	Betweenness centrality	→	Doctoral students' h-index	1.83	0.45	4.10	<0.001	0.29	Supported
H3c	Student-mentor coauthorship count	→	Doctoral students' h-index	0.25	0.05	4.69	<0.001	0.33	Supported
H3d	Doctoral students' partnership ability index	→	Doctoral students' h-index	0.62	0.12	5.31	<0.001	0.38	Supported
H4a	Mentors' h-index	→	Closeness centrality	0.01	0.00	3.03	<0.01	0.19	Supported
H4b	Mentors' h-index	→	Degree centrality	0.01	0.00	2.40	<0.05	0.10	Supported
H5a (3)	Doctoral students' coauthor count	→	Degree centrality	0.01	0.00	7.05	<0.001	0.33	Supported
H5b (3)	Doctoral students' coauthorship unit count	→	Degree centrality	0.04	0.00	11.95	<0.001	0.55	Supported
H5d (3)	Doctoral students' partnership ability index	→	Degree centrality	0.07	0.02	3.34	<0.01	0.25	Supported
H6a	Degree centrality	→	Betweenness centrality	0.96	0.05	19.08	<0.001	1.01	Supported
H1a	Mentors' h-index	→	Doctoral students' h-index	0.02	0.02	1.22	0.22	0.05	Not Supported
H1b	Mentors' fecundity	→	Doctoral students' h-index	0.01	0.01	1.63	0.10	0.09	Not Supported
H2a	Closeness centrality	→	Doctoral students' h-index	−0.35	0.59	−0.59	0.56	−0.02	Not Supported
H2c	Degree centrality	→	Doctoral students' h-index	0.54	0.55	0.97	0.33	0.09	Not Supported
H3a	Doctoral students' coauthor count	→	Doctoral students' h-index	−0.01	0.01	−0.60	0.55	−0.03	Not Supported
H3b	Doctoral students' coauthorship unit count	→	Doctoral students' h-index	0.01	0.03	0.51	0.61	0.03	Not Supported
H5a (1)	Doctoral students' coauthor count	→	Closeness centrality	0.00	0.00	0.81	0.42	0.06	Not Supported
H5a (2)	Doctoral students' coauthor count	→	Betweenness centrality	0.00	0.00	1.50	0.13	0.06	Not Supported
H5b (1)	Doctoral students' coauthorship unit count	→	Closeness centrality	0.00	0.00	0.33	0.74	0.03	Not Supported
H5b (2)	Doctoral students' coauthorship unit count	→	Betweenness centrality	−0.01	0.00	−1.98	<0.05	−0.10	Not Supported
H5c (1)	Student-mentor coauthorship count	→	Closeness centrality	0.00	0.01	0.27	0.79	0.03	Not Supported
H5c (2)	Student-mentor coauthorship count	→	Betweenness centrality	−0.02	0.01	−2.74	<0.01	−0.17	Not Supported
H5c (3)	Student-mentor coauthorship count	→	Degree centrality	−0.03	0.01	−2.78	<0.01	−0.21	Not Supported
H5d (1)	Doctoral students' partnership ability index	→	Closeness centrality	0.01	0.01	0.94	0.35	0.11	Not Supported
H5d (2)	Doctoral students' partnership ability index	→	Betweenness centrality	−0.04	0.02	−2.67	<0.01	−0.17	Not Supported
H6b	Closeness centrality	→	Betweenness centrality	−0.09	0.08	−1.06	0.29	−0.04	Not Supported

Note: UnStd. = unstandardized path coefficients, S.E. = standard error, C.R. = critical ratio, and Std. (β) = standardized path coefficients.



e

	Quantile 0.05	Quantile 0.15	Quantile 0.25	Quantile 0.35	Quantile 0.45	Quantile 0.55	Quantile 0.65	Quantile 0.75	Quantile 0.85	Quantile 0.95
Betweenness centrality	1.28**	1.25**	2.01**	2.34**	2.49**	2.71**	2.81**	2.40**	3.19**	3.82**
	(11.13)	(5.97)	(8.70)	(12.79)	(12.77)	(15.98)	(18.71)	(13.84)	(19.12)	(17.11)
Student-mentor coauthorship count	-0.14**	0.07	0.18**	0.17**	0.24**	0.36**	0.37**	0.39**	0.40**	0.31*
	(-3.63)	(1.66)	(4.75)	(4.32)	(5.99)	(8.72)	(8.41)	(7.10)	(5.13)	(2.19)
Doctoral students' partnership ability index	0.82**	0.49**	0.54**	0.72**	0.68**	0.50**	0.52**	0.63**	0.74**	1.13**
	(12.05)	(6.35)	(6.02)	(8.03)	(7.74)	(5.76)	(5.65)	(5.89)	(4.88)	(4.31)
Mentors' tenure	-0.04	-0.00	-0.00	-0.00	0.00	0.01	-0.00	0.00	-0.01	-0.05*
	(-1.63)	(-0.00)	(-0.00)	(-0.00)	(0.03)	(0.49)	(-0.13)	(0.10)	(-0.60)	(-2.34)
Constant	0.27	0.45	0.27	0.11	0.17	0.30	0.55	0.60	0.84*	1.65**
	(0.64)	(1.01)	(0.63)	(0.31)	(0.50)	(0.96)	(1.83)	(1.81)	(2.12)	(4.30)
N	237	237	237	237	237	237	237	237	237	237
R^2	0.24	0.35	0.39	0.47	0.50	0.53	0.54	0.55	0.55	0.57

* p<0.05, ** p<0.01 (t value)

Fig. 3 Quantile regression of variables on the h-index. a. Betweenness centrality; **b**. Student-mentor coauthorship count; **c**. Doctoral students' partnership ability index; **d**. Mentors' tenure; **e**. Results of quantile regression analysis.

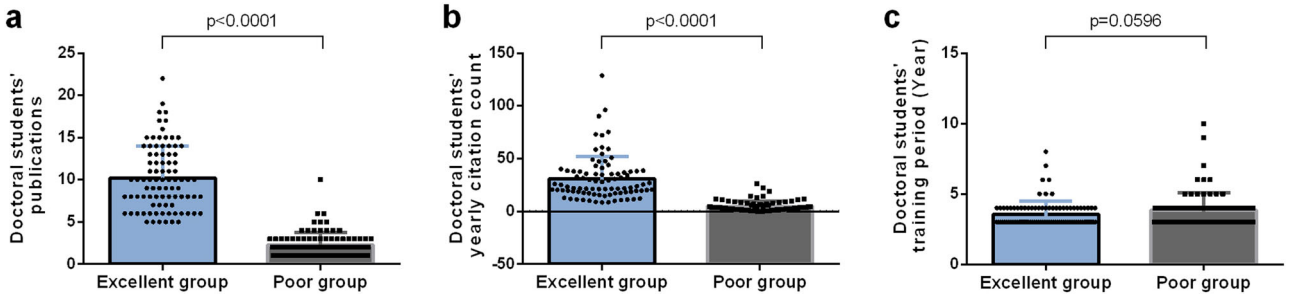


Fig. 4 Differences in the variables between the excellent and poor groups. a. Doctoral students' publications; **b**. Doctoral students' yearly citation count; **c**. Doctoral students' training period.

doctoral students' publications, 6% of the papers ($n = 85$) were published in 2021, which may have affected the *h-index*. As a further robustness check, we ran a regression selecting the number of doctoral students' publications as the dependent variable. The results were consistent with the main findings of this study, which confirms the important role of *betweenness centrality*, the *partnership ability index*, and *student-mentor coauthorship count* in the dependent variable (see Table S2).

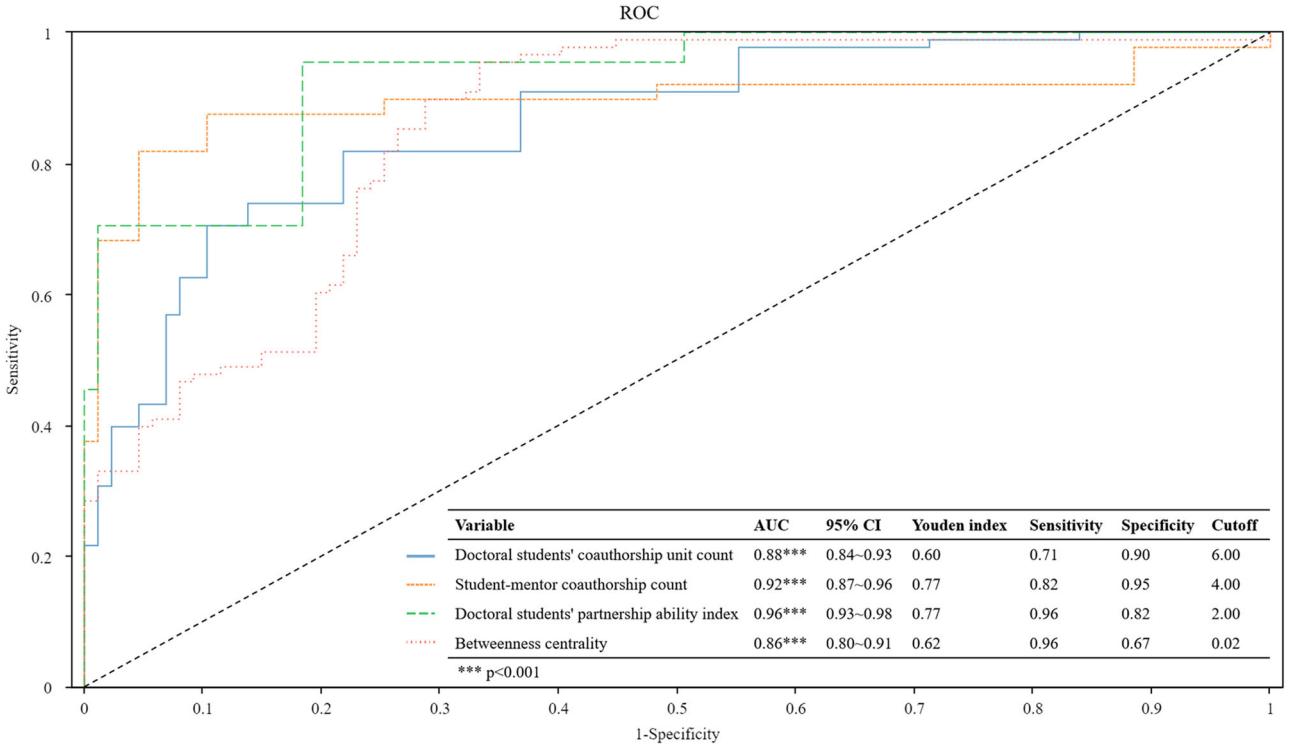


Fig. 5 ROC curves of the variables.

Discussion

In this study, we investigate the relationship between coauthorship networks and the research impact of medical doctoral students from a social capital perspective. Research impact has complex connotations, including the changes it brings to academia and beyond, such as social, economic and environmental benefits (Bærøe et al. 2022; Belcher and Halliwell, 2021). In academia, research impact demonstrates the contribution of quality research to academic advances in theory and application, and publications as research outcomes reflect this impact (Greenhalgh et al. 2016). This study focused on publications by doctoral students, as these are almost universal research outputs that students generate during their studies, thus facilitating comparisons with each other, but it may have ignored whether their research produced more value in fields outside academia. Although publications and impact indicators do not represent the full research competence of a person or institution, they are easy to quantify and obtain and not easily affected by personal subjective judgment, which makes them widely accepted and used for comparison and ranking between universities or individuals in the context of increasingly fierce quality competition (Musselin, 2018). This also leads to a focus on the published papers and impact index of doctoral students in their training without guiding the students to develop needed competencies in the implementation process. In this study, publications and the *h-index* were all obtained from the WoS database, which includes almost all global scientific documents and provides high-quality and continuously updated data to meet the needs of scientific research (Birkle et al. 2020) and as a result was a reliable data source. The results confirmed the positive influence of coauthorship on the research impact of doctoral students, which reflects the importance of cooperation in the development of doctoral students' research competence. This is a necessary supplement to the core competence that medical students should possess under a competency-based medical education model and should receive increased attention from the government or at the university level (Leiphrakpam and Are, 2023).

Deepening the understanding of the role of mentorship, this study provides evidence that mentorship enhances the research impact of doctoral students by furnishing favorable social capital through their coauthorship networks. Previous studies have shown that the greater a mentor's research impact is, the better the research performance of her or his postgraduates is. For example, mentors who are themselves Nobel Prize winners often cultivate more future Nobel Prize winners (Chariker et al. 2017). This may lead doctoral students to choose mentors with high academic performance, resulting in the Matthew effect of the "rich get richer" in science (Perc, 2014). However, our research suggests that the *student-mentor coauthorship count* and the *partnership ability index* of relational capital and the *betweenness centrality* of structural capital are the main factors that have a positive effect on the *h-index*. We did not find a direct influence of *mentors' h-index* on *doctoral students' h-index*, which is in contrast to Jing Shang's research (Shang et al. 2022). This finding indicates that it is very important for doctoral students to maintain trusting and committed relationships with their mentors to increase their relational capital first. In addition to providing professional and emotional support to doctoral students, mentors should guide them in scientific cooperation. In addition, this suggests that doctoral students should consider the selection of mentors more comprehensively rather than being determined by mentors' research impact, which may be more conducive to the establishment of good mentorship and also bring more equitable opportunities for young menors or those in disadvantaged disciplines to recruit students.

To increase their coauthorship, the quantile regression indicated that the top 5% of doctoral students with an *h-index* above 9 should focus on strengthening cooperation with different researchers and increasing their control over resources in the coauthorship network to achieve more innovation breakthroughs rather than relying on cooperation with their mentors, which is similar to the advice for scholars in Xu and Chang's study (Xu

and Chang, 2020). Close relationships with their mentors can lead to exclusivity and leave no space for others to collaborate, which is not conducive to innovation (Liu-Lastres and Cahyanto, 2023). Furthermore, the *partnership ability index* reflects strong ties between coauthors rather than simply increasing the number of collaborators, enabling better research performance. This is also consistent with the findings of (Abbasi et al. 2011). In addition, we confirmed the negative effect of *mentors' tenure* on the *h-index* of doctoral students, which is consistent with previous research on citations (Corsini et al. 2022). Specifically, students in the top 5% of the *h-index* may experience some negative effects, and the impact on the remaining students can be ignored.

This study revealed that the *betweenness centrality* positively affected the *h-index*, but degree and closeness centralities did not have any significant effect, which is similar to Eldon Y. Lia's research on scholars' citation counts (Li et al. 2013). The greater the *betweenness centrality* of a doctoral student is, the stronger his or her ability to control information and resources beyond other persons in the network is (Xu and Chang, 2020). There were significant positive relationships between *betweenness centrality* and both *degree centrality* ($r_s = 0.81$, $p < 0.01$) and *closeness centrality* ($r_s = 0.65$, $p < 0.01$). This result is consistent with those of previous studies, but these studies did not explain the influence relationship between them (Abbasi et al. 2011; Li et al. 2013; Xu and Chang, 2020). We further confirmed that only *degree centrality* had a significant positive effect on *betweenness centrality* ($\beta = 1.01$, $p < 0.001$), whereas *closeness centrality* had no significant effect. Moreover, *degree centrality* was significantly positively affected by the *coauthor count*, *coauthorship unit count*, the *partnership ability index* of a doctoral student, and *mentors' h-index*, especially the *coauthorship unit count* ($\beta = 0.55$, $p < 0.001$), which had the greatest effect. This is because *degree centrality* is a measure of the number of collaborators (Lu and Feng, 2009). Therefore, increasing the number of coauthors and coauthorship units of doctoral students not only directly affects *degree centrality* but also indirectly enhances *betweenness centrality* to increase their research impact.

Additionally, we found that the *student-mentor coauthorship count*, the *partnership ability index* and *betweenness centrality* had significant predictive effects on the *h-index*. In particular, increasing the *partnership ability index* and *betweenness centrality* greatly increased a student's likelihood of having high research impact. Specifically, doctoral students whose *partnership ability index* is greater than 2, whose *student-mentor coauthorship count* is greater than 4, whose *coauthorship unit count* is greater than 6, and whose *betweenness centrality* is greater than 0.02 have high productivity. The results have some practical implications for mentors, doctoral students, and educational institutions. As role models for doctoral students, mentors should be good at cooperating with others; building teams; and creating an atmosphere of fairness, trust and respect so that doctoral students can integrate into the teams quickly and establish good cooperative relationships with team members. Additionally, mentors should assume the responsibility for developing students' collaborative capacity and help them expand their cooperation networks with individuals, teams and relevant industries through different research projects (Gisbert, 2017). For doctoral students, establishing a win-win mode of thinking, viewing colleagues as potential partners rather than competitors, and learning to coexist and develop harmoniously with others should be a recommended value orientation for their growth (Zhang et al. 2021). Educational institutions should promote the scientific cooperation of doctoral students at the organizational level, providing policy and financial support to address barriers to intersectional and multidisciplinary cooperation (Leenaars et al. 2015). Moreover, these cooperation indicators should be included in the evaluation system to track doctoral students' research performance to identify and cultivate future stars in academia earlier.

Limitations of the study. This study has several limitations. First, we used the *h-index* as the only dependent variable representing the research impact, and more indicators from funds, patents and technology transfer may be further used to confirm these results. Meanwhile, nine independent variables were explored via SCT. Although structural capital is well explained by the three centrality measures, other measures may better reflect relational capital and cognitive capital. For example, relational capital may be further measured by students and their mentors' ranking on the author list of an article (Xie et al. 2022). The research theme similarity between students and mentors can also be considered a direction for exploring the relationship between cognitive capital and research impact in the future (Liénard et al. 2018). Moreover, the results reveal the influence of *degree centrality* and *betweenness centrality* in structural capital on the *h-index*, but the effect of *closeness centrality* should be considered in further research. Second, this study is based on 237 medical doctoral students who graduated from two Chinese universities from 2016–2021 and their mentors, which may hinder the generalizability of the results to other periods or disciplines. Future studies could generalize these findings by replicating studies in multiple disciplines using larger datasets and longer study periods. Third, there is a growing need for interdisciplinary research in academia. This study examined the impact of increasing the number of cooperative units on the research impact of doctoral students, while different cooperative units may indicate the diversity of the subject majors of the collaborators. It is necessary to further verify the differences in social capital resulting from interdisciplinary and multiprofessional cooperation and their effects on students' research impacts in future studies.

Conclusion

This study defines nine independent variables from doctoral students' coauthorship network based on three dimensions of social capital theory and examines how these indicators interact, influence, and predict *doctoral students' h-index*. The results show that utilizing social capital from coauthorship networks, especially *betweenness centrality*, *student-mentor coauthorship count* and the *partnership ability index*, is an effective way to increase the research impact of medical doctoral students. The results show the important role of collaboration in improving doctoral research competence and deepen the understanding of good mentorship in doctoral students' development. Most importantly, they provide several strategies for harnessing social capital for relevant organizations, mentors and doctoral students who want to increase their research impact. First, cooperation in cultivating doctoral students should be considered, and the shaping of cooperative spirit, norms and skills in education should be strengthened. Second, more abundant cooperation resources for doctoral students should be provided, and a smoother cooperation platform through policy orientation and administrative intervention should be built to promote the cross-unit cooperation mode among multiple scholars with strong connections. Third, a concrete and feasible development plan should be created according to the judgment criteria and predictive value of the indicators. For example, a *partnership ability index* greater than 2 inspired us to believe that doctoral students should have a team of at least 3 mentors from different institutions at the beginning of their schooling to accelerate collaboration and promote research impact. Meanwhile, doctoral students should strengthen communication with their mentors, maintain good teacher–student

relationships, and enhance their personal ability to obtain information and resources in coauthorship networks. Doctoral students with high *h-index* levels should not rely on mentors but should expand their scope of cooperation, actively cooperate with different scholars from different institutions, and strengthen their cooperative relationships.

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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Author contributions

GC: Investigation; Data curation; Formal analysis; Writing - original draft. W-WY: Investigation; Data curation; Formal analysis. X-YW: Investigation; Data curation. QN: Formal analysis. YX: Data curation. XM: Conceptualization; Supervision. J-JY: Conceptualization; Formal analysis; Funding acquisition; Project administration; Writing - review & editing. All authors approved the final manuscript.

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The authors declare no competing interests.

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Additional information

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Correspondence and requests for materials should be addressed to Juan-Juan Yue.