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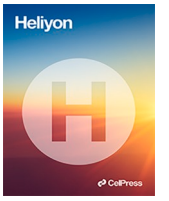

Research article

Digital finance, financial regulation and transformation of R&D achievements

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ABSTRACT

The transformation of scientific and technological achievements is the best form of the combination of technology and the economy, and only when new technologies are transformed into commodities can they be transformed into real productive forces and exert scale effects. With the rapid development of digital finance, it has changed the operating mode of financial markets and consumer behavior. Does digital finance promote the transformation of R&D achievements? We empirically examine this question using the panel data covering 30 provinces in China from 2011 to 2021. The empirical results indicate that the development of digital finance can improve the transformation rate of R&D achievements. Additionally, we find that the role of digital finance in promoting the transformation of R&D achievements needs to be guaranteed by the level of effective financial regulation. The research conclusions are a relevant reference for the government to improve the transformation rate of scientific and technological achievements.

1. Introduction

The transformation of transformation of research and development (R&D) achievements is an important part of national innovation and development strategies. It is also the key link in strengthening the close combination of science and technology and the economy, which is usually called the commercialization stage of R&D innovation. The fact is that the transformation of R&D achievements has attracted increasing interest from all walks of life because it will bring obvious competitive advantages to regional economic development once R&D achievements are successful [1,2]. The broader literature examining the transformation of R&D achievements mainly focuses on the difficulties, key barriers to and solutions for the transformation of R&D achievements [3–7], and some scholars argue that the transformation of scientific and technological achievements requires adequate financial support from governments, industries, and other stakeholders [5,8,9]. Additionally, the effect of government intervention in China is more obvious than that in Western countries [10] [-] [12]. In reality, the highest transformation rate of scientific and technological achievements in China is just 30 % because of lacking adequate funds and investment [13]. Therefore, adequate financial resources have been recognized as an important determinant of the transformation of scientific and technological achievements in China [1,5]. However, the high output uncertainty, irreversibility and long cycles characterize the transformation of R&D achievements, which means that it is difficult to obtain sufficient financial support from traditional financial market in China [14]. Thus, there is an urgent need to find efficient and low-cost financial services to improve the transformation rate of R&D achievements in China.

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Recently, with the rapid development of digital technology in terms of artificial intelligence, mobile internet, big data, block-chain, cloud computing and so on, a new financial model named digital finance has come into being, including traditional financial institutions and internet companies use digital technology to realize financing, payment, investment and other new financial business models [15], attracting the attention of many scholars [16,17]. Specifically, on the one hand, digital finance is characterized by inclusiveness, low costs, low thresholds and strong geographical penetration, which makes the financial supply more extensive and can provide more convenient financial services for more technological innovation players [11,18], which can improve the availability of financial services for the transformation of R&D achievements. On the other hand, digital finance is a double-edged sword, and financial risks still exist, especially driven by digital technologies, digital financial risks have become more unpredictable and controllable. The combination of new financial risks and traditional financial risks makes the spread, correlation, and amplification effects of risks more significant [19,20], which leads to an increase in the level of risk borne by the subject of scientific and technological achievements transformation, and hinders the transformation of scientific and technological achievements. Based on this, the key issue that this article aims to address is: can digital finance promote the transformation of technological achievements? Further, if digital finance risk regulation is strengthened, can digital finance better promote the transformation of technological achievements?

Consequently, we take the provincial-level data from China as the research sample and construct panel Tobit models and panel threshold models to test the relationship between digital finance and the transformation of R&D achievements. The results indicate that digital finance can promote the transformation of R&D achievements in China. In addition, financial regulation needs to be controlled within a reasonable range to leverage the advantages of digital finance. That is, the role of digital finance in promoting the transformation of R&D achievements needs to be guaranteed by the level of effective financial regulation. Our findings contribute to better utilizing the advantages of digital finance and improving the conversion level of R&D achievements.

The contributions of this study are as follows. First, this research enriches the theory of financial support for technological innovation activities and expands the literature of technological achievements transformation. In fact, the transformation of scientific and technological achievements is an important content and stage of innovation activities, but the existing literature mostly studies innovation activities from the perspectives of R&D stage [21–23], with relatively little research on innovation activities in the technology achievements transformation stage. There is even less research on the combination of digital finance and transformation of R&D achievements.

As its second contribution, this paper uses the BCC-DEA model to calculate the transformation efficiency of scientific and technological achievements transformation as the proxy variables for the level of the transformation of R&D achievements, including both input and output concepts of scientific and technological achievements, which is more relevant and scientific than using new product quantities or sales revenue to measure the level of technological achievements conversion in existing research [2,24,25], and makes the conclusion more robust.

Third, we believe that digital finance has not changed the essence of finance, and financial risks still exist, especially driven by new technologies, which makes the spread effect, correlation effect and amplification effect of risks more significant [22]. Therefore, we introduce the variable of financial regulation to further analyze the relationship between digital finance and the transformation of R&D achievements and test the nonlinear effect of digital finance on the transformation of R&D achievements under different levels of financial regulation through a threshold panel model. Compared to prior literature [26–28], we not only consider the positive impact of digital finance, but also the negative impact it brings, which helps us better utilize the advantages of digital finance to drive innovation activities.

The paper is organized as follows: Section 2 provides the hypotheses development of the relationship between digital finance and the transformation of R&D achievements. Section 3 the empirical model and describes the data used to test the model. Section 4 conducts the empirical analysis, including the effect of digital finance on the transformation of R&D achievements and threshold effect between digital finance and the transformation of R&D achievements. Section 5 provides the discussion and conclusions.

2. Hypotheses development

2.1. The relationship between digital finance and transformation of R&D achievements

The core content of the transformation of R&D achievements is to test whether R&D achievements with practical value can be successfully transformed into new products as well as the market acceptance of these new products. Not only is it necessary to have sufficient capital to invest as support, but it is also necessary to bring new products to the market and test the market's recognition and acceptance of these new products. That is, the transformation rate of scientific and technological achievements will be affected not only by capital investment but also by regional market consumption.

Firstly, digital finance has competitive effect. Digital finance is a new type of financial service provided through digital technology, which can provide more financial products and services, reduce the cost of capital acquisition, promote the efficiency improvement of financial institutions, and form a competitive effect in the financial market [29]. Specifically, there are large number of financial resources with characteristics such as large, small, and scattered in the financial market, which are excluded by traditional financial institutions due to high absorption costs and complex procedures. However, digital finance can absorb these idle financial resources in a low-cost, fast, and convenient way and convert them into market financial supply [19], which increases the financial supply of the entire financial market and intensifies the competitiveness of traditional financial markets. Thus, the competitive effect of digital finance has increased the availability of funds for the transformation of R&D achievements.

Secondly, digital finance has financial product innovation effect. Digital finance breaks the time and space constraints between financial resource demanders and financial resource suppliers, so that financial resource suppliers can reach more financial

demanders, and financial resource demanders can also access credit funds more conveniently through online financial services, easing the credit constraints the transformation of R&D achievements [29,30]. Importantly, digital finance excavates various historical behavioral data of financial service demanders through a series of emerging technologies, comprehensively sorts and analyzes them, forms reports on the market development potential and technological innovation ability of financing demanders, and designs personalized financial products [31]. Financial products created by digital finance avoid credit reports and collateral becoming essential for obtaining financing, lower the financing threshold of the credit market, and enable more financial resource demanders excluded by traditional financial institutions to access financial services [32–34]. Thus, the financial product innovation effect of digital finance has increased the availability of funds for the transformation of R&D achievements.

Thirdly, digital finance has the effect of alleviating information asymmetry between credit parties. Digital finance relies on information technology to process large amounts of data at low cost, conveniently, and quickly, comprehensively mining the historical behavioral data of credit fund demanders, providing more reference information for credit fund providers, greatly improving the information collection ability of finance as an intermediary, and effectively alleviating the information asymmetry phenomenon between borrowers and lenders [26,35–37], which could improve the availability of funds for the transformation of R&D achievements.

Additionally, digital finance can change residents' payment habits and consumption expectations. For example, digital payment not only simplify the payment process and procedures but also eliminate the temporal and spatial obstacles to payment by consumer, reduce consumers' payment costs, and greatly improve consumers' consumption utility [23,38]. In doing so, digital finance not only provides market information for the transformation of R&D achievements but also provides market opportunities for the consumption of new products and improves the efficiency of the transformation of R&D achievements.

Thus, this brings the first hypothesis that is as follow.

H1. Digital finance can improve the transformation of R&D achievements.

2.2. The role of financial regulation

The essence of digital finance is still finance, and its financial risks still exist. The development of digital finance is driven by new technologies that make the spread effect, correlation effect and amplification effect of risks more significant [19,28]. The reason is that technological innovation is like a double-edged sword that not only accelerates the development of digital finance but also constitutes an important source of risk [19]. That is, only by reasonably avoiding digital financial risks can we better utilize the advantages of digital finance. Experience has shown that effective financial regulation can avoid financial risks and maintain normal financial order [39]. But we also should pay attention to the rationality of financial regulation and avoid excessive financial regulation, which can lead to a decrease in credit availability for the transformation of scientific and technological achievements, which is not conducive to the transformation of scientific and technological achievements. That is to say, the effective financial regulation is a prerequisite and guarantee for giving full play to the advantages of digital finance. A perfect financial regulation system can effectively reduce the probability of digital financial risks by reasonably allocating financial resources and accurately monitoring financial risks. Therefore, we introduce the financial regulation to further explore the relationship between digital finance and the transformation of R&D achievements. We set our second hypothesis as follows:

H2. When financial regulation is within a reasonable range, the higher the level of financial regulation, the more significant the role of digital finance in promoting the transformation of R&D achievements; when there is excessive financial regulation, it will suppress the promoting effect of digital finance on the transformation of R&D achievements.

3. Data and estimation strategy

3.1. Data sources

This study selects panel data covering 30 provinces (and municipalities and autonomous regions) excluding Xizang, Hong Kong, Macao and Taiwan in China from 2011 to 2021 as the research sample, and it discusses the relationship between digital finance and the transformation of R&D achievements. Xizang was excluded from the sample because of incomplete data; Hong Kong, Macao and Taiwan were excluded from the sample because their units of measurement and statistical calibre differ from those of other regions in China. Additionally, all variables in this study are winsorized at the 1 % level and 99 % level at both tails of their distribution to eliminate the influence of extreme values in the data on the regression estimation results.

The relevant indicators for measuring the level of digital finance come from the National Bureau of Statistics and China statistical yearbook on science and technology. The data on the transformation level of scientific and technological achievements, the consumption scale, the regional economic growth rate, financial regulation, the educational level, the urbanization level, infrastructure and fund input are obtained from the National Bureau of Statistics. Other credit availability and open-level data used in this study are obtained from the WIND database.

In addition, to consider the long-term nature of the commercialization of R&D achievements and alleviate the influence of endogeneity, this paper deals with the independent variable and control variables by means of a one-period lag.

3.2. Definitions of the key variables

3.2.1. Dependent variable

In this study, the dependent variable is the transformation level of scientific and technological achievements (*trans_tech*), which is defined as the process of the scientific and technological achievements testing, small-scale transformation into new products and market entry. Thus, we use the BCC-DEA model to calculate the transformation efficiency of scientific and technological achievements transformation as a proxy variable for the dependent variable in this paper [40]. The specific calculation formula is as follows:

$$trans\_tech = \max\left(\mu^T y_{rj} + \mu_i\right) / \nu^T x_{ij} \tag{1}$$

$$s.t. \begin{cases} \mu^T y_{rj} + \mu_i - \nu^T X_j \le 0, j = 1, 2, \ldots n \\ \mu \ge \varepsilon e_a, \nu \ge \varepsilon e_m, \mu \in R \end{cases} \tag{2}$$

The μ^T and ν^T in expression (1) represent the weight vectors of the input and output of R&D transformation activities respectively; x_{ij} and y_{rj} refer the input and output of R&D achievements respectively. The detailed indicators for measuring the R&D achievements transformation are shown in Table 1 [41].

3.2.2. Independent variable

Most studies use the Digital Inclusive Finance Index published by the Digital Finance Research Center of Peking University, which comes from the Alipay ecosystem, and reflects the digital financial information of residents and micro and small enterprises [42,43]. In fact, the subject of technological achievements transformation discussed in this paper also includes many large enterprises. Thus, we measure the development level of regional digital finance from three aspects: digital financial services, digital financial technology and the digital financial environment [44]. Specifically, digital financial services are the foundation for achieving digital finance, mainly reflecting the extent to which the region can provide digital financial services; digital financial technology is the technological driving force for the development of digital finance; the digital financial environment mainly reflects the environmental foundation of digital financial operation and is the guarantee for the operation of digital finance. Therefore, this study primarily uses the total index of digital finance (*df*), digital financial services(df_1), digital financial technology(df_2) and the digital financial environment(df_3) as the proxy variable for digital finance. Additionally, the proxy variables of digital finance are logarithmically processed to eliminate data volatility. The detailed indicators for measuring the development level of digital finance are shown in Table 2.

3.2.3. Threshold variable

Based on the previous theoretical analysis, the threshold variable in this study is the level of financial regulation (*supervision*). Following the research of Tang et al. (2020) [19], this study uses the proportion of financial regulation expenditure in the general budget expenditure of local public finance as the proxy variable for the level of financial regulation. Meanwhile, to eliminate the influence of the quantity level on the estimation results, this ratio is expanded by 1000 times.

3.2.4. Control variables

According to the existing literature, the regional economic growth rate (*gdp_rate*), the educational level (*edu*), the industrial structure (*stru*), the urbanization level (*urb*), the level of government support (*gov*), the openness level (*open*), and the level of marketization (*market*) are also factors that affect the transformation of technological achievements [1,5,13,45]. Thus, we use these variables as control variables for this paper. In addition, the definitions of these variables are presented in Table 3.

3.3. Model specification

When using the DEA method to calculate the efficiency value, if the value is greater than 1, the value is 1, which means that the part where the efficiency value is greater than 1 is truncated. Thus, we select the panel Tobit model to effectively solve the truncation problem of the dependent variable [45].

$$\text{trans\_}tech_{it} = \alpha_0 + \alpha_1 df_{it-1} + \sum \beta_j \text{Control}_{\text{ijt}-1} + \mu_{t-1} + \nu_i + \varepsilon_{it-1} \tag{3}$$

In Equation (3), *Control* represents the control variables noted above; i represents the province under study; t refers to the year of analysis (from the 2011–2021 time periods); μ and ν represent the time and individual effects, respectively; and ε is the random error

Table 1
Measurement indicators of the R&D achievements transformation.

input indicators	The numbers of R&D papers
	The total number of patent authorizations
	The numbers of invention patent authorizations
	The new product development funds
output indicators	The numbers of new products
	Sales revenue of new products
	New product export revenue

Table 2
Measurement indicators of digital finance

Major indexes	Minor indexes	Calculation method
Digital financial services	Total telecom service volume	Total telecom service volume
	Total postal service volume	Total postal service volume
	Digital financial consumption	The total retail sales of social consumer goods*Internet penetration
Digital financial technology	Number of digital financial services staff	Financial industry practitioners
	Number of FinTech enterprises	Number of FinTech-related enterprises
	Number of patents granted	Number of patents granted related to digital finance
	R&D spending	public finance technology spending
	Number of R&D staff	Computer Services and Software Industry Practitioners
	The scale of digital financial enterprises	Market value of listed digital financial companies
Digital financial environment	Total mobile phone users	Number of mobile phone users
	Total Internet users	Number of Internet broadband users
	Digital finance concerns	Web Crawler from Baidu Index
	Digital financial policy support	Text Analysis
	Region light index	Region light image

Source: Liao, G., Li, Z., Wang, M., 2022. Albitar, K. Measuring China's urban digital finance. Quantitative Finance and Economics.6, 385–404.

Table 3
Definitions of the main variable.

Type	Variable	Notation	Definition
dependent variable	transformation of R&D achievements	*trans_tech*	transformation efficiency of scientific and technological achievements
independent variable	total index of digital finance	*df*	ln(total index of digital finance)
	digital financial services	df_1	ln(digital financial services)
	digital financial technology	df_2	ln(digital financial technology)
	digital financial environment	df_3	ln(digital financial environment)
mechanism variable	credit availability	*credit*	the ratio of the loan balance to deposit balance of financial institutions
	consumption scale	*cons*	ln(per capital household consumption)
threshold variable	financial regulation	*supervision*	(the proportion of financial regulation expenditure in the general budget expenditure of local finance)*1000
control variable	economic growth rate	*gdp_rate*	the growth rate of real GDP
	educational level	*edu*	ln(the number of students in colleges and universities)
	industrial structure	*stru*	the proportion of added value of the second and third industries to GDP
	urbanization level	*urb*	the percentage of the urban population to the total population
	government support	*gov*	the proportion of government science and technology expenditure to total expenditure
	openness level	*open*	(amount of foreign investment actually used * exchange rate)/GDP
	marketization	*market*	the marketization index calculated by Fan Gang et al.

term.

In addition, we construct the following panel threshold model to test the impact of digital finance on the transformation of R&D achievements under different levels of financial regulation.

$$trans_{tech_{it}} = \lambda_0 + \lambda_1 df_{it-1} \times I(\sup ervision \leq r) + \lambda_2 df_{it-1} \times I(\sup ervision > r) + \sum \varphi_j X_{ijt-1} + \mu_{t-1} + \nu_i + \varepsilon_{it} \quad (4)$$

Table 4
Descriptive statistics of the main variables in the model.

Variable	Obs	Mean	S.D.	Min	Max
trans_tech	330	0.207	0.207	0.160	1.000
df	330	4.714	0.110	4.637	5.370
df_1	330	4.904	0.016	4.893	4.997
df_2	330	4.742	0.019	4.729	4.852
df_3	330	4.550	0.023	4.534	4.681
credit	330	1.263	0.021	1.228	1.323
cons	330	9.641	0.387	8.735	10.728
supervision	330	0.01	0.014	0.000	0.102
gdp_rate	330	0.015	0.030	−0.089	0.135
edu	330	4.258	0.800	1.520	5.518
stru	330	0.901	0.053	0.742	0.997
urb	330	0.590	0.122	0.350	0.896
gov	330	0.021	0.015	0.004	0.068
open	330	0.019	0.019	0.000	0.125
market	330	7.852	1.917	3.360	12.922

in Equation (4), $I(\cdot)$ represents the indicative function in the threshold regression model. If the expression in the bracket is true, the value is 1; otherwise, the value is 0. r is the actual threshold value of the threshold regression model.

4. Empirical results

4.1. Descriptive statistics

The descriptive statistics of the main variables in the model are presented in Table 4, showing that the transformation level of R&D achievements in China is low, and the development of digital finance in China is relatively rapid. Therefore, it is necessary to study the impact of digital finance on the transformation of R&D achievements.

In addition, the heatmap in Fig. 1 represents the matrix of the Pearson and Spearman correlation coefficients between the transformation of R&D achievements and digital finance. This paper mainly analyses the Spearman correlation coefficient between variables. As shown in upper right triangle of Fig. 1, the correlation coefficient between the transformation of R&D achievements and the total index of digital finance, the digital financial services, the digital financial technology, the digital financial environment is significantly positive. However, this correlation does not eliminate the mixed effects of other variables. Thus, it is necessary to further explore the quantitative relationship between the transformation of R&D achievements and digital finance.

4.2. Baseline regression

The results of Model (3) are the baseline regression results of this paper, showing in Table 5 below. Columns (1), (2), (3) and (4) report the regression results of the total index of digital finance, digital financial services, digital financial technology and digital financial enviroment on the transformation of R&D achievements respectively.

As shown in Table 5, the total index of digital finance with a one-period lag (L.*df*) has a significant and positive effect on the transformation of R&D achievements in Column (1), showing that digital finance can improve the transformation rate of scientific and technological achievements. Nevertheless, these results cannot reflect the influence of the different dimensions of digital finance on the transformation of scientific and technological achievements. Columns (2), (3) and (4) show that coefficients of digital financial services with a one-period lag (L.df_1), digital financial technology with a one-period lag (L.df_2) and digital financial environment with a one-period lag (L.df_3) are still positive and significant at the 1 % level. These results provide empirical evidence for Hypothesis 1 (H1).

Regarding the effect of the control variables on the transformation of scientific and technological achievements, it is vividly shown in Table 5. In column (1), the coefficients of economic growth rate with a one-period lag (L.*gdp_rate*), government support with a one-period lag (L.*gov*), marketization with a one-period lag (L.*market*) are insignificant at 10 % level. The coefficients of educational level with a one-period lag (L.*edu*), industrial structure with a one-period lag (L.*stru*), urbanization level with a one-period lag (L.*urb*) are positive and significant ($p < 0.1$), showing the higher the educational level, industrial structure and urbanization level, the higher the

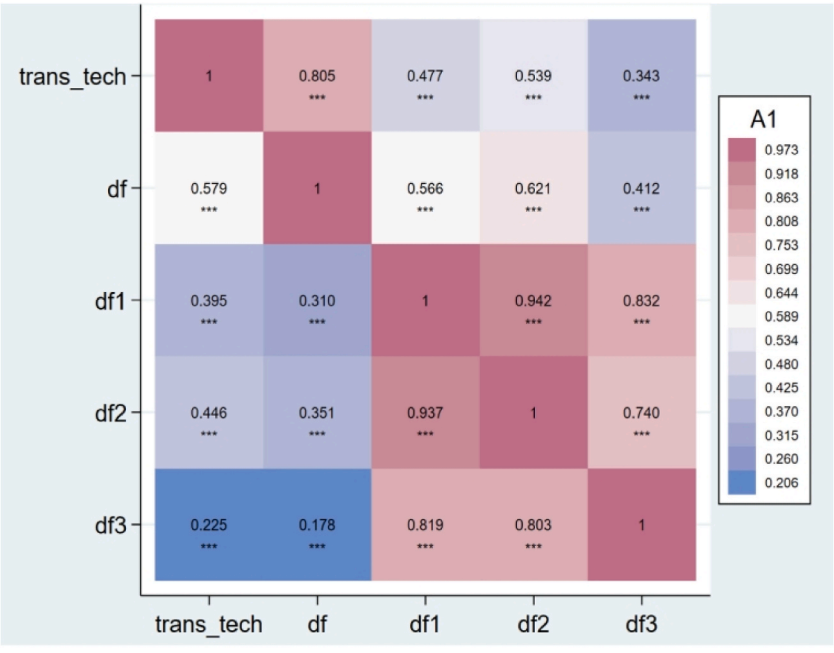

Fig. 1. The heatmap of the matrix of correlation coefficients between variables. Note: the upper right triangle is the Spearman correlation coefficients, and the lower left triangle is the Pearson correlation coefficients; $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

Table 5
Baseline regression results.

	(1)	(2)	(3)	(4)
L.*df*	1.177*** (0.424)			
L.df_1		1.469*** (0.471)		
L.df_2			2.938*** (0.942)	
L.df_3				0.734*** (0.236)
L.*gdp_rate*	0.016 (0.381)	0.101 (0.382)	0.107 (0.381)	0.103 (0.385)
L.*edu*	0.360* (0.189)	0.420* (0.222)	0.420* (0.222)	0.417* (0.221)
L.*stru*	3.058** (1.232)	4.029*** (1.395)	4.059** (1.400)	4.029*** (1.395)
L.*urb*	2.948** (1.229)	4.132*** (1.400)	4.029*** (1.400)	4.132*** (1.400)
L.*gov*	−1.204 (2.584)	−1.504 (2.731)	−1.504 (2.731)	−1.504 (2.591)
L.*open*	−2.837** (1.156)	−3.569** (1.210)	−3.566** (1.428)	−3.794** (1.152)
L.*market*	−0.007 (0.007)	−0.007 (0.007)	−0.007 (0.007)	−0.007 (0.007)
Constant	80.123*** (34.505)	124.595*** (40.789)	121.657*** (40.039)	133.396** (40.884)
Individual effect	Yes	Yes	Yes	Yes
Time effect	Yes	Yes	Yes	Yes
Wald chi2	78.460***	83.490***	83.490***	83.400***
Obs.	300	300	300	300

Note: Standard errors in parentheses; *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

transformation rate of scientific and technological achievements. In addition, there is a significantly negative relationship between L.*open* and *trans_tech*. Meanwhile, the coefficients of the control variables in columns (2), (3) and (4) are all consistent with the estimation result of column (1).

4.3. Endogeneity analysis

There are still omitted variables that can affect the transformation of R&D achievements, which may result in a deviation of the estimation results from reality and a lack of credibility. Therefore, we need to select appropriate instrumental variables (IVs) to eliminate endogeneity bias. The literature believes that the closer to Hangzhou, the faster the development of digital finance because Hangzhou is the financial technology industry highland and is the home city of financial technology enterprises such as Alibaba and Ant Financial Services [46]. Hence, the distance from the provincial city to Hangzhou is often used as an IV of digital finance [47]. The distance from the provincial city to Hangzhou does not change over time. Following Yang and Zhang (2022) [47] and Gao and Wang (2023) [48], we construct an interaction term between the distance from the provincial city to Hangzhou and the mean value of the digital financial development index for other provinces (cities, autonomous regions) in the same year as an IV of digital finance (*IV*). Then, we conduct IV-tobit model analysis to alleviate endogeneity bias, and the estimation results are shown in Table 6.

As shown in Table 6, the coefficients of *IV* are positive and significant at the 1 % level in columns (1)–(4), and the coefficients of the total index of digital finance with a one-period lag (L.*df*), digital financial services with a one-period lag (L.df_1), digital financial technology with a one-period lag (L.df_2) and digital financial environment with a one-period lag (L.df_3) are still positive and significant at the 5 % level, which is consistent with the estimated results in Table 5. That is, the estimation results in Table 5 are still robust after controlling for endogeneity.

4.4. Robustness tests

Additionally, this paper selects the sub-sample interval from 2014 to 2021 to test the robustness of the relationship between digital finance and the transformation of R&D achievements, because most people regard the launch of yu'e Bao in 2013 as the first year of digital finance development in China [15]. As shown in Table 7, the estimation results are still positive and significant ($p < 0.01$) at the

Table 6
Endogeneity estimation results.

	(1)	(2)	(3)	(4)
L.*df*	1.407*** (0.317)			
L.df_1		1.418*** (0.229)		
L.df_2			1.500*** (0.293)	
L.df_3				1.355** (0.481)
IV	2.526*** (0.792)	2.070*** (0.945)	2.518*** (0.790)	1.305*** (0.693)
control variable	YES	YES	YES	YES
Individual effect	YES	YES	YES	YES
Time effect	YES	YES	YES	YES
_cons	8.792*** (1.308)	8.897*** (1.320)	8.538*** (1.294)	8.651*** (1.303)
Wald	28.01***	33.93***	45.33***	19.26***
Obs	300	300	300	300

Note: Standard errors in parentheses; *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

Table 7
Estimation results of the robustness tests (Sub-sample from 2014 to 2021)

	(1)	(2)	(3)	(4)
L.*df*	1.972*** (0.523)			
L.df_1		2.625*** (7.16)		
L.df_2			5.251*** (1.431)	
L.df_3				1.313*** (0.358)
Control Variable	Yes	Yes	Yes	Yes
Individual Effect	Yes	Yes	Yes	Yes
Time Effect	Yes	Yes	Yes	Yes
Wald chi2	96.87***	119.90***	107.51***	90.82***
Obs.	210	210	210	210

Note: Standard errors in parentheses; *p < 0.1, **p < 0.05, ***p < 0.01.

1 % level, which are consistent with the baseline regression results in Table 5, further demonstrating the robustness of the empirical evidence of robustness for Hypothesis 1 (H1).

4.5. Analysis of the threshold characteristics of financial regulation

We construct a threshold panel model with the level of financial regulation as the threshold variable to further test the relationship between digital finance and the transformation of R&D achievements. The threshold test result shows double threshold values, and threshold estimation results are shown in Table 8. In Column (1), the coefficient of the total index of digital finance with a one-period lag (L.*df*) is positive but nonsignificant when financial regulation is below the first threshold value of 0.007, the coefficient is positive and significant at 10 % level when financial regulation is between the first threshold value of 0.007 and the second threshold value of 0.608, and the coefficient is naegative but nonsignificant when financial regulation is above the second threshold value of 0.608, showing that the role of digital finance in promoting the transformation of R&D achievements is more obvious under a reasonable level of financial regulation. That is, whether the level of financial regulation is too high or too low, it is not conducive to leveraging the advantages of digital finance and promoting the transformation of R&D achievements. Meanwhile, the estimation results of Columns (2), (3) and (4) once again show that the role of digital finance in promoting the transformation of R&D achievements needs to be guaranteed by the level of effective financial regulation, which provides empirical evidence of robustness for Hypothesis 2 (H2).

5. Discussion and conclusions

5.1. Research conclusions and implication

The transformation of scientific and technological achievements is an important component of innovation activities and a stage of innovation activity [1,49]. It has the characteristics of high risk and high return and requires a large amount of funds [13]. Meanwhile, the financial industry has experienced a continuous evolution in service delivery due to the rapid rise of digital technology, and a new financial model named digital finance has come into being. The competitive effect, financial product innovation effect and the effect of alleviating information asymmetry between credit parties of digital finance not only improve the availability of financial services for market participants but also change the payment habits and consumption habits of market participants [29,38], bringing new possibilities to the financial market, which may affect innovation activity. The existing literature mostly studies innovation activities from the perspectives of R&D stage [21–23], with relatively little research on innovation activities in the technology achievements transformation stage. Thus, this paper constructs a panel fixed effect model and a panel threshold model to study the impact of digital finance on the transformation of R&D achievements using data covering 30 provinces (and municipalities and autonomous regions) in China from 2011 to 2021, which enriches the theory of financial support for technological innovation activities. The main results and conclusions are as follows.

First, the development of digital finance can improve the transformation rate of R&D achievements. In our study, the total index of digital finance with a one-period lag, digital financial services with a one-period lag, digital financial technology with a one-period lag and digital financial environment with a one-period lag can significantly improve the level of commercialization of scientific and technological achievements. Then, a series of robustness tests indicate that the estimation results are robust, which validates hypothesis 1(H1).

Second, the relationship between digital finance and the transformation of R&D will change with the level of financial regulation. Specifically, when financial regulation is within a reasonable range, the higher the level of financial regulation, the more significant the role of digital finance in promoting the transformation of R&D achievements; when there is excessive financial regulation, it will suppress the promoting effect of digital finance on the transformation of R&D achievements. That is, the positive role of digital finance in the transformation of scientific and technological achievements needs to be guaranteed by the level of effective financial regulation, which is consistent with hypothesis 2(H2).

Based on the above research conclusions, the following insights can be drawn:

Table 8
Estimation results of the threshold characteristics of financial regulation.

Independent variable	(1)	(2)	(3)	(4)
	L.*df*	L.df_1	L.df_2	L.df_3
Threshold1	0.007	0.007	0.007	0.007
Threshold2	0.608	0.608	0.608	0.608
range1	0.100 (0.060)	0.073 (0.050)	0.080 (0.059)	0.068 (0.045)
range2	0.132** (0.060)	0.108** (0.048)	0.112* (0.058)	0.081* (0.045)
range3	−0.036 (0.060)	−0.029 (0.049)	−0.033 (0.058)	−0.021 (0.045)
Control variables	Yes	Yes	Yes	Yes
Constant	8.746*** (1.205)	8.864*** (1.113)	8.467*** (1.109)	8.751*** (1.200)
*Adj_*R^2	0.538	0.536	0.536	0.536
Obs.	300	300	300	300

Note: Standard errors in parentheses; *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

(1) Digital finance, as a new type of financial service, has changed the mode of financial ecosystem services and has a significant impact on fund demanders. The government should take a series of measures to encourage the whole society to widely use digital financial products and promote the digital transformation of traditional financial institutions [15].
(2) With the deep integration and development of finance and technology, the boundary between finance and technology has become more blurred. It is necessary to balance the relationship between technological innovation and financial risk, which poses new requirements for the financial regulatory system. In fact, it's not that the stricter the regulation, the better the development of the financial market [39]. The relevant departments should conduct reasonable supervision of digital finance and promote the healthy development of digital finance, which also poses new requirements for financial regulatory agencies.

5.2. Research deficiencies

In the contex of rapid development of digital technology, this paper explores whether digital finance can promote transformation of R&D achievements, and the threshold effect of financial regulation, which is a very important topic. However, there are some limitations to this study that can be addressed in future research. Firstly, constrained by the availability of research data, the measurement of digital financial indicators is not precise and sufficient, especially in the measurement of digital technology. Secondly, the existing research mainly explores financial support for research and development activities, and the theoretical analysis of the impact on the transformation of scientific and technological achievements is relatively rare, resulting in relatively limited research. The mechanism by which digital finance affects the transformation of scientific and technological achievements needs to be further expanded and enriched. Thus, the prospect of future research is to pay attention to the theoretical relationship between digital finance and the transformation of technological achievements, and to measure digital finance more reasonably, to better reflect the regional differences and overall situation of digital finance development in China.

CRediT authorship contribution statement

Zhengjuan Xie: Writing – original draft, Methodology, Data curation. **Yongchao Wu:** Writing – review & editing, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

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

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