

Research on the Mechanism of Industrial Robots and Enterprise Innovation Enhancement

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Abstract

With the continuous progress of science and technology, industrial robots play an increasingly important role in the industrial field. The widespread application of industrial robots not only improves production efficiency, reduces labor costs, but also enhances product quality. In order to study the effect of investing in industrial robots on enhancing corporate innovation, this article uses data from listed manufacturing companies from 2011 to 2019 to empirically test the impact of industrial robot application on corporate innovation. Research has found that the application of industrial robots has a significant promoting effect on the innovation performance of enterprises; Mechanism research has found that promoting corporate innovation behavior is mainly achieved through upgrading human capital and investing in research and development; Further research has found that this promoting effect is more significant in samples of large-scale, high productivity, and state-owned enterprises. Therefore, in order to promote enterprises to enhance their innovation capabilities and cultivate new competitive advantages, the government should actively promote industrial robot application policies, increase research and development investment intensity, and promote the intelligent development of manufacturing enterprises.

Keywords

Industrial Robots; Enterprise innovation; R&D investment; Human Capital.

1. Introduction

Robots are known as the "jewel at the top of the manufacturing industry's crown", and their research and development, manufacturing, and application are important indicators to measure a country's level of technological innovation and high-end manufacturing. In the context of a new round of technological revolution and industrial transformation, major economies around the world are actively engaging in fierce competition around the intelligent manufacturing industry dominated by industrial robots. In 2016, the State Council of China launched the "Made in China 2025" plan, which listed robots as one of the strategic emerging industries. In 2017, the Ministry of Industry and Information Technology issued the "Development Plan for the New Generation of Artificial Intelligence Industry", which clearly stated the need to accelerate the development of intelligent and highly integrated robots. At the same time, we will accelerate the promotion of automation transformation and encourage enterprises to adopt high-end equipment technologies such as industrial robots to improve the intelligence level of production lines. On the one hand, it encourages enterprises to increase research and development investment, providing technical support for the development of the robotics industry. On the other hand, it actively promotes the development of the robotics industry, strengthens industry norms and standard management, and expands the development space of various industries.

With the widespread application of digitalization and intelligent technology, promoting the development of industrial intelligence has become an important driving force for a new round

of technological revolution. Continuously promoting corporate innovation capability is an important guarantee for China to implement an innovation driven strategy. In the early stages of production development, manufacturing enterprises use machines to extend human hands, replacing physical labor with low technological content, high labor intensity, and high risk factors (Zhu Qiaoling and Li Min, 2017). With the continuous deepening of information technology development, robot technology is constantly moving towards the direction of intelligent simulation of human partial intelligence and sensation. At present, robots have the ability to further recognize, judge, make decisions, and comprehend human commands, assisting enterprises in completing various control and information processing tasks, further replacing people's "semi mental" labor (Zhu Jiantian, 2020). With the increasing popularity of robot applications, low skilled labor costs can be saved, which can further promote enterprises to increase investment in research and development activities. The increase in research and development investment may bring new products and technologies to enterprises, further promoting the improvement of innovation performance (Yun Hong et al., 2021).

The impact of robot applications on the improvement of enterprise innovation performance comes from the impact of information technology development on innovation performance. Joshi et al. based on the ACAP theory, concluded that enterprises can increase their knowledge and capabilities through the application of information technology, which is beneficial for generating new products and services. Currently, there is little literature on the impact of the widespread promotion of industrial robots on enterprise innovation and improvement. However, from a long-term development perspective, with the disappearance of China's "demographic dividend", increasing labor costs, and a series of policy incentives to promote the transformation and upgrading of the manufacturing industry, the application of industrial robots in China has considerable prospects. The large-scale introduction of robots for automated production by enterprises will inevitably bring about significant changes in their future development.

On this basis, this article is based on the data of listed manufacturing companies from 2011 to 2019, and examines the impact of industrial robot applications on enterprise innovation improvement at the enterprise level.

2. Theoretical Analysis and Research Hypotheses

With the improvement of automation technology, industrial robots are constantly undergoing intelligent upgrades and transformations. Promote the integration of existing resources by enterprises to continuously integrate robots with their production processes, equipment, and products, further achieving innovation in production processes and products, and injecting vitality into improving enterprise innovation performance (Huang Haiyan et al., 2023). Therefore, this article proposes hypothesis 1:

H1: The application of industrial robots has a significant promoting effect on enhancing enterprise innovation.

Another literature study investigated the substitution effect of industrial robots on labor force. They found that when companies use industrial robots, there is an increased demand for high skilled and low skilled labor, while the impact on medium skilled labor is not significant (Autor and Dorn, 2013). From the perspective of labor income, the use of artificial intelligence has a substitution effect on low skilled labor, while there is a complementary effect with high skilled labor (Wang Linhui et al., 2020). Therefore, with the widespread promotion and use of industrial robots, the demand for low skilled labor has decreased, and the demand for high skilled labor has increased, resulting in a change in the demand for labor skills and promoting the transformation and upgrading of human capital structure (Han Ying and Xu Xuelu, 2023). This article proposes hypothesis 2:

H2: Using industrial robots to enhance human capital upgrading and drive enterprise innovation.

R&D investment expenditure (R&D) reflects the participation of enterprises in innovation activities from the perspective of investment, and is another important indicator for measuring enterprise innovation activities. Robots have various advantages such as low error rate, high efficiency, and high safety. With the improvement and development of information technology, the price of using robots is becoming more and more economical (Li Min and Huang Haiyan, 2022). The widespread application of industrial robots generally reduces production costs and improves efficiency. This cost savings can be used to increase research and development budgets and promote the development of innovative projects. Using robots for production can also improve product quality, enhance production capacity, further increase market competitiveness, occupy more market share, and bring more income for research and development, increasing the intensity of research and development investment. Therefore, this article proposes hypothesis 3:

H3: The application of industrial robots promotes the intensity of R&D investment and enhances enterprise innovation behavior.

3. Model Variables and Data

3.1. Econometric Model

In order to identify the role of using industrial robots in enhancing corporate innovation behavior, we constructed the following model for research and analysis at the enterprise level.

$$LNNO = \alpha_0 + \alpha_1 Exposure + \alpha_2 X_{i,j,c,t} + \mu_i + \delta_j + \sigma_t + \varphi_c + \varepsilon_{i,j,c,t} \quad (1)$$

Among, i, j, c, t representing enterprise, industry, city, and year respectively, the dependent variable is enterprise innovation, is the influence coefficient, is the control variable, is the fixed effect of enterprise and industry, represents the fixed effect of year, represents the fixed effect of city, and is a random disturbance term. It is the estimated coefficient of the core explanatory variable, which reflects the impact of using industrial robots on corporate innovation behavior and is the focus of this article.

3.2. Variable Definition

3.2.1. The Dependent Variable

This article uses the number of patent applications as a measure of corporate innovation. The specific approach is to add 1 to the number of patent applications and then take the logarithm to represent it.

3.2.2. Core Explanatory Variables

Referring to the calculation method of Wang Yongqin and Dong Wen (2023), "robot penetration" is used as a measurement indicator for "industrial robot applications". The specific measurement methods are as follows:

The first step is to calculate the penetration rate of robots at the industry level, denoted as $Robot_{it}^{CH}$:

$$Robot_{it}^{CH} = \frac{MR_{it}^{CH}}{L_{i,t=2010}^{CH}} \quad (2)$$

Among them, MR_{it}^{CH} is the stock of industrial robots in the Chinese industry for the year, $L_{i,t=2010}^{CH}$ represents the employment number of the Chinese industry based on 2010, and $Robot_{it}^{CH}$ is the penetration rate of industrial robots in the Chinese industry for the year.

The second step is to calculate the penetration rate index of industrial robots at the enterprise level:

$$robots_{ijt} = \frac{PWP_{jit=2011}}{ManuPWP_{t=2011}} \times \frac{MR_{it}^{CH}}{L_{i,t=2010}^{CH}} \tag{3}$$

$\frac{PWP_{jit=2011}}{ManuPWP_{t=2011}}$ represents the ratio of the proportion of production department employees in manufacturing industry enterprises based on 2011 to the median proportion of production department employees in all manufacturing enterprises in 2011. Then, this proportion is used as a weight to decompose the penetration of industrial robots at the industry level into the enterprise level, in order to measure the penetration of industrial robots at the enterprise level. $robots_{ijt}$ represents the penetration rate of industrial robots by industry enterprises in the year.

3.2.3. Control Variables

Referring to previous literature, this article selects enterprise size (Size), enterprise age (FirmAge), asset liability ratio (Lev), total asset growth rate (Gra), total asset profit margin (Roa), and capital intensity (Capital) as control variables.

3.3. Data Source

Table 1. Descriptive Statistics of the Main Explanatory Variables

Variable Name	Definition	Sample	Mean	Sd	Min	Max
INNO	Enterprise patent application plus logarithm of 1	14098	1.51	1.54	0.00	9.84
Exposure	Take the logarithm of $robots_{ijt}$	10297	2.33	1.85	-7.92	6.41
Size	Take the logarithm of total assets	14791	21.95	1.17	17.64	27.47
FirmAge	Add 1 to the difference between the observation year and the year of establishment of the enterprise and take the logarithm	14791	2.82	0.34	1.10	4.13
Lev	Total liabilities/total assets	14791	0.39	0.20	0.01	1.45
Gra	(Total assets of the current period - total assets of the previous period)/total assets of the previous period * 100%	14790	0.21	0.51	-0.93	18.39
Roa	Net profit/total assets	14791	0.04	0.07	-1.24	0.38
Capital	Total assets/operating income	14791	2.20	3.42	0.13	289.89

This article takes Chinese listed companies as the research object and selects data on manufacturing listed companies from 2011 to 2019. In order to ensure the representativeness and validity of the data sample as much as possible, we refer to existing literature and exclude ST and PT enterprises from the sample data. The robot data comes from the database published by the International Federation of Robotics (IRF). We matched the robot database with the database of listed companies in the manufacturing industry, and finally obtained 14791 "company annual" samples. The descriptive statistical results of the main variables are shown in Table 1.

From the descriptive statistical results of the main variables in Table 1, the mean penetration rate of robots is 2.33, with a standard deviation of 1.85. This indicates that the level of robot application in enterprises is not high, and there is a significant difference in robot penetration rates among different enterprises; The average value of enterprise innovation performance is 1.51, indicating that the overall innovation level of Chinese enterprises is relatively low, with a standard deviation of 1.54, indicating a significant gap in innovation capabilities among enterprises.

4. Empirical Result Analysis

4.1. Benchmark Regression

To identify the relationship between the use of industrial robots and corporate innovation behavior, we conducted regression tests on model (1) using high-dimensional fixed effects, and the results are shown in Table 2. In (1), without adding control variables, while controlling for firm fixed effects, year fixed effects, industry fixed effects, and city fixed effects, the results show that the core estimation coefficient is positive at the 1% significance level; (2) Added control variables at the firm level, only controlling for firm fixed effects, year fixed effects, and industry fixed effects; The third column adds urban fixed effects on the basis of the second column, and the results still show that the core estimation coefficient is significantly positive at the 1% level. This fully demonstrates that the use of industrial robots has enhanced enterprise innovation. The research hypothesis H1 proposed in this article has been preliminarily validated.

Table 2. Benchmark Regression Results

Variable	(1)	(2)	(3)
Exposure	0.0791***	0.0753***	0.0741***
	(0.0281)	(0.0279)	(0.0281)
Size		0.0229	0.0244
		(0.0451)	(0.0456)
FirmAge		0.0820	0.0757
		(0.2046)	(0.2073)
Lev		0.1538	0.1894
		(0.1202)	(0.1210)
Gra		0.0011	0.0002
		(0.0148)	(0.0150)
Roa		-0.2453*	-0.3044**
		(0.1371)	(0.1380)
Capital		-0.0038**	-0.0038**
		(0.0016)	(0.0018)
Cons	1.4612***	0.6874	0.6620
	(0.0659)	(1.0517)	(1.0656)
Industry	YES	YES	YES
Firm	YES	YES	YES
Year	YES	YES	YES
City	YES	NO	YES
Number	9728	9732	9728
R2	0.880	0.879	0.880

Note: ***, **, * significantly at statistical levels of 1%, 5%, and 10%, respectively; The robust standard error clustered to the enterprise level is shown in parentheses.

4.2. Robustness Testing

In order to ensure the reliability of the conclusions drawn in this article and further illustrate the promoting effect of industrial robot application on the improvement of enterprise innovation behavior, considering that the characteristic factors of the company in the current year may have an impact on enterprise technological innovation and generate endogeneity problems, this article will conduct robustness tests on industrial robot application data with a lag of one year and two years, respectively. The regression results are shown in Table 3. Table 5 column (2) lagged the penetration rate data of enterprise industrial robots by one year, with an estimated coefficient of 0.0421 for the explanatory variable, which passed the 5% significance level. Table 5 column (3) lagged the penetration rate data of industrial robots by two years, with a core estimated coefficient of 0.0431, which passed the 5% significance level. This fully demonstrates that the conclusion drawn in this article is robust, and the use of industrial robots has a significant positive promoting effect on the improvement of enterprise innovation behavior.

Table 3. Robustness Testing

	(1)	(2)	(3)
Variable	Main Effect	Lagged by one period	Lagged by Two period
Exposure	0.0741*** (0.0281)	0.0421** (0.0211)	0.0431** (0.0208)
Size	0.0244 (0.0456)	0.0360 (0.0445)	0.0162 (0.0455)
FirmAge	0.0757 (0.2073)	-0.1000 (0.2266)	-0.0182 (0.2658)
Lev	0.1894 (0.1210)	0.2403** (0.1187)	0.2308* (0.1203)
Gra	0.0002 (0.0150)	-0.0322 (0.0200)	-0.0239 (0.0165)
Roa	-0.3044** (0.1380)	-0.2371* (0.1390)	-0.2579* (0.1415)
Capital	-0.0038** (0.0018)	-0.0025* (0.0015)	-0.0016 (0.0011)
Cons	0.6620 (1.0656)	1.0504 (1.0815)	1.3397 (1.1721)
Industry	YES	YES	YES
Firm	YES	YES	YES
Year	YES	YES	YES
City	YES	YES	YES
Number	9728	8514	7412
R2	0.880	0.900	0.915

4.3. Mechanism Analysis

4.3.1. Upgrade of Human Capital

The use of industrial robots has changed traditional production methods, replaced some low skilled labor, and promoted industrial structure upgrading. On the other hand, it has spawned production tasks with cutting-edge technology, which requires labor to have strong abilities in machine learning and natural language processing (Han Ying and Xu Xuelu, 2023). Therefore, the substitution and enhancement effects of the use of industrial robots have a reverse effect

on the learning of new knowledge by the labor force. In order to better apply industrial robot technology, enterprises need to introduce and cultivate talents with specialized skills in robot programming, operation, and maintenance. In this process, it has promoted the upgrading of human capital. We use the proportion of graduate education or above to the total number of employees to represent the high skilled labor force of the company, and then construct an interaction term with the penetration rate of robots, which is included in the model for regression. The results are shown in column (1) of Table (3), and the estimated coefficient of the interaction term is significantly positive at the 1% level, indicating that human capital upgrading promotes the improvement of industrial robots in enterprise innovation.

4.3.2. R&D Investment Intensity

R&D investment is one of the main sources for enterprises to carry out innovation activities. Increasing the intensity of R&D investment provides financial support for enterprises to attract more scientific research talents, and can also prepare sufficient funds for enterprises to purchase advanced scientific research equipment, create a good research environment, and promote the improvement of enterprise innovation performance. With the continuous progress of industrial robot technology, enterprises will increase their investment in research and development of robot technology in order to maintain their competitive advantage. Through continuous R&D investment, enterprises can master more advanced industrial robot application technology, promote deep integration of industrial robots and production processes, further optimize production processes, improve production efficiency and product quality. Furthermore, in order to better utilize the efficiency of industrial robots, enterprises need to introduce advanced information and intelligent technologies, build modern production lines and intelligent factories. Therefore, the popularization of industrial robot applications is also forcing enterprises to innovate in technology and management. We measure the intensity of R&D investment by the proportion of R&D investment amount to the total revenue of the enterprise, and then include it in the regression with the interaction term formed by robot penetration rate. The results are shown in (2), where the coefficient of the interaction term is significantly positive at the 5% level, fully demonstrating that the increase in R&D investment promotes the use of industrial robots in promoting enterprise innovation behavior.

Table 4. Mechanism Analysis

Variable	(1)	(2)
Exposure	0.0423	0.0503*
	(0.0380)	(0.0297)
Exposure*High_skill	0.9167***	
	(0.2783)	
Exposure*RD		0.6107**
		(0.2486)
Cons	1.3414	1.2766
	(1.4008)	(1.0699)
Industry	YES	YES
Firm	YES	YES
Year	YES	YES
City	YES	YES
Number	6555	9487
R2	0.893	0.881

5. Further Research: Heterogeneity Analysis

5.1. Analysis of Heterogeneity in Enterprise Productivity

There are differences in the application process of industrial robots among enterprises with different productivity levels. In high productivity enterprises, they have more resources and energy invested in innovation activities. In enterprises with low productivity, excessive reliance on industrial robots for simple and repetitive production activities may lead to slow improvement of employee skills, which is not conducive to innovation activities. We use total factor productivity to represent the level of enterprise productivity and construct a median of total factor productivity to divide enterprise productivity into high and low types. The regression results are shown in column (1) of Table 4, and the estimated coefficient of the interaction term is significantly positive, fully proving our expectations.

5.2. Heterogeneity Analysis of Ownership

There are significant differences in policy support and resource allocation between state-owned and non-state-owned enterprises, which can affect their innovation behavior. When state-owned enterprises introduce and apply industrial robot technology, they often make full use of the atmosphere of national policy support and technological innovation, have more resources and opportunities to introduce industrial robot technology, and accelerate the transformation and upgrading of traditional manufacturing to high-end intelligent manufacturing. At the same time, state-owned enterprises face relatively fewer institutional constraints in introducing advanced equipment and technology, and their decision-making processes are more flexible, which is conducive to quickly responding to market changes and technological development trends. Therefore, we will construct a dummy variable SOE based on the ownership attributes of the enterprise, with a value of 1 for state-owned enterprises and 0 for non-state-owned enterprises. Then, an empirical test of the interaction term was constructed, and the results are shown in column (2) of Table 4. The coefficient of the interaction term is significantly positive, indicating that industrial robots have a more significant effect on enhancing innovation in state-owned enterprises.

5.3. Analysis of Heterogeneity in Enterprise Scale

Table 5. Heterogeneity Analysis

Variable	(1)	(2)	(3)
Exposure	0.0574** (0.0286)	0.0471* (0.0282)	0.0672** (0.0281)
Exposure*TFP	0.0391*** (0.0152)		
Exposure*SOE		0.1081*** (0.0246)	
Exposure*Size			0.0244** (0.0118)
Cons	1.0289 (1.0850)	-0.0867 (1.0716)	1.1805 (1.1190)
Industry	YES	YES	YES
Firm	YES	YES	YES
Year	YES	YES	YES
City	YES	YES	YES
Number	9728	9728	9728
R2	0.880	0.881	0.880

From the perspective of enterprise scale, there are significant differences between large enterprises and small and medium-sized enterprises in the application of industrial robots for enterprise innovation. For large enterprises, their economies of scale are significant, and they usually have sufficient funds and technological strength to invest in the research and application of industrial robots, effectively improving production efficiency and enhancing product quality. At the same time, it has the ability to build complex production lines and intelligent factories, deeply integrate industrial robots and other advanced technologies, and promote innovative development of enterprises in the era of intelligent manufacturing. In this regard, we conducted regression analysis on enterprises divided into two sizes: large and small. The results of (3) showed that the interaction coefficient was significantly positive, indicating that the application of industrial robots in large-scale enterprises has a more significant promoting effect on enterprise innovation behavior.

6. Conclusion and Recommendations

Industrial robots, as a technological embodiment of the development of artificial intelligence, have a significant impact on the transformation and upgrading of China's manufacturing industry, as well as enhancing innovation capabilities and development levels. This article delves into the impact and mechanism of robot penetration rate on the improvement of enterprise innovation performance, and concludes that the promotion and use of industrial robots have a positive promoting effect on the improvement of enterprise innovation; The conclusion of mechanism analysis indicates that promoting enterprise innovation is mainly achieved through upgrading human capital and increasing R&D investment intensity; Heterogeneity analysis shows that in large enterprises, high productivity levels, and state-owned enterprises, the promotion effect is more significant. In the context of the development of intelligent manufacturing, using robots and automatic equipment to replace human labor can promote employees to improve their skills, thereby enhancing their competitiveness and innovation ability. The mechanism of its action is that the use of robots can increase the intensity of research and development investment, thereby improving the innovation level of enterprises. Mainly because enterprises use robots to replace labor to save a lot of labor costs, and robots have high production efficiency, low cost, and high safety. Their products are more competitive in the market, bringing more profit margins, and more funds are invested in research and development, providing financial support for enterprises to enhance their innovation capabilities.

The conclusion drawn in this article has important research implications. Enterprises should actively respond to the national call for the vigorous promotion of industrial robots and improve their robot application level. Technological innovation is a key element for enterprises to improve market competitiveness. Industrial robots, as the concentrated embodiment of the new generation of intelligent manufacturing technology, are a manifestation of innovation progress. Therefore, manufacturing enterprises should further improve their robot application level. For enterprises with insufficient innovation motivation, if they do not want to be eliminated by the market and establish themselves in the market, the role of industrial robot application in enhancing enterprise technological innovation is more obvious. At the same time, building a sound industrial robot application ecosystem and promoting innovation and upgrading of the entire industry chain. Enterprises not only need to adopt industrial robots in the production and manufacturing process, but also extend their full lifecycle management to front-end design and development, mid-range intelligent manufacturing, and back-end service support, forming a robot application model that covers the entire value chain. While encouraging the implementation of policies related to robot applications, the government also provides certain tax incentives and policy subsidies to small and medium-sized enterprises

with insufficient innovation, enabling them to have the ability and funds to participate in innovation activities. It also recognizes and distributes bonuses to researchers and companies who have made innovative contributions, stimulating innovation vitality. In terms of talent development, the government should increase efforts to cultivate and introduce talents in the field of industrial robots. Through establishing special funds, building industry university research cooperation platforms, and other means, enterprises, universities, and research institutions should be encouraged to match and cultivate professional talents, creating an internationally competitive team of industrial robot research and application talents.

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