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WHY HAVE R&D-INTENSIVE INDUSTRIES IN JAPAN EXPERIENCED A RECENT DECLINE IN PERFORMANCE? EVIDENCE FROM PANEL DATA OF LISTED FIRMS IN JAPANESE R&D-INTENSIVE INDUSTRIES

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Abstract. Previous studies show that the rate of return on research and development (R&D) capital is high. However, R&D-intensive industries in Japan have recently experienced a decline in performance. This study estimates the rate of return on R&D capital and physical capital as well as total factor productivity (TFP) to solve this puzzle. The rate of return is properly estimated applying the methods, which deal with simultaneity bias issues. After Japan entered the "lost decade", the rate of return on R&D capital dropped significantly, while the rate on physical capital did not. This trend cannot be found by the methods without considering the issues, typically used in previous studies. The slowdown of TFP growth occurs coincidentally with a declining rate of return on R&D capital, which suggests the importance of innovations that enable effective use of R&D capital. Considering the trends, the declining rate of return on R&D capital along with the slowdown of TFP growth are the main causes of the low performance of recent R&D-intensive industries. The results of this paper also offer suggestions on economic policies and growth strategies.

Keywords: research and development (R&D), rate of return on R&D capital, rate of return on physical capital, simultaneity, production function, total factor productivity (TFP), R&D-intensive industries, Japanese firms, growth strategy.

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Introduction

Research and development (R&D) capital is thought to be at the core of technological progress. Most previous studies show that the rate of return on R&D capital is high. However, recent R&D-intensive industries in Japan[1] have experienced a decline in performance. The average annual growth of real value added and labour productivity for listed firms in Japanese R&D-intensive industries are shown in Table 1. The annual growth rate is divided into three periods: the bubble period (1986–1990), the "lost decade" (1991–2001)[2], and the period "after the lost decade" (2002–2010). The growth rate of value added declined significantly after 1991, except for pharmaceutical firms, which declined after 2002. It is worth noting that the average rate for R&D-intensive industries is lower than that for the manufacturing industry after 2002. The growth rate of labour productivity for R&D-intensive industries follows the same trend as that of value added. It has long been said that the strength of Japanese manufacturing firms lies in R&D capability[3]. Why then have R&D-intensive industries in Japan experienced a recent decline in performance?

Table 1. Average annual growth of real value added and labor productivity by industry

	Value added			Labor productivity		
	1986–1990	1991–2001	2002–2010	1986–1990	1991–2001	2002–2010
a. Pharmaceutical	4.4%	5.0%	0.4%	6.1%	6.7%	2.9%
b. Electric and Electronic	12.1%	1.6%	0.5%	12.1%	5.3%	1.5%
c. Chemical	2.7%	–1.5%	–2.4%	5.3%	2.2%	–1.1%
d. Machinery	8.0%	–0.8%	–3.7%	9.3%	2.7%	–3.2%
e. R&D intensive (a + b + c + d)	7.7%	0.2%	–1.7%	8.8%	3.6%	–0.8%
f. Manufacturing	5.6%	–1.1%	0.5%	5.9%	0.9%	1.0%

Note: For R&D intensive industries (a. to e.), value added and labour productivity are calculated using the financial statements of Japanese listed firms. For manufacturing (f), they are adapted from the Financial Statements Statistics of Corporations by Industry, the Ministry of Finance. Labour productivity is calculated by value added per employees.

[1] The average ratio of R&D expenses to total sales can be calculated using data from the Survey of Research and Development for 2015 by the Statistics Bureau, the Ministry of Internal Affairs and Communications. The results show that the ratio is 26% for pharmaceutical, 10% for electric and electronic, 6% for chemical, 11% for machinery and only 3% for all other firms except for finance and insurance firms.

[2] The 1990s, considered a decade of economic stagnation, are generally called the "lost decade" for the Japanese economy (see Hayashi, Prescott 2002; Kneller *et al.* 2012).

[3] The World Competitiveness Yearbook by Institute for Management Development (IMD) reports that Japan shows significant strength in the scientific infrastructure category, coming second to the United States in recent years. The scientific infrastructure index mainly consists of quantitative aspects of R&D activities by public and private sectors. We will also focus on the qualitative aspects of R&D capital.

The purpose of this paper is to investigate the underlying factors behind the recent decline in the performance of R&D-intensive industries in Japan. Toward that end, the rate of return on the R&D and physical capital of Japanese listed firms in R&D-intensive industries is measured. Very few studies have provided empirical evidence using data from after 2000. The rates of return on both capitals are properly estimated through production function[4] with methods that deal with simultaneity bias issues, which few previous studies consider. By using the estimated parameters, the total factor productivity (TFP) is calculated to confirm whether there is in fact active innovation[5]. The results of this paper will also form the bases for considering economic policy and growth strategy.

The remainder of this paper is organised as follows. In Section 1, previous studies are reviewed. Estimation methods are considered in Section 2. The rate of return on R&D and physical capital as well as the TFP of Japanese firms in the R&D-intensive industries are estimated and the main findings of the paper are discussed in Section 3.

1. Previous studies

Most previous studies measuring the returns on R&D capital rely on a production function framework, which contains R&D capital. It is assumed to be that as used in studies such as Hall and Mairesse (1995) as follows:

$$Y_{jt} = AL_{jt}^{\beta_L} K_{P,jt}^{\beta_P} K_{R,jt}^{\beta_R} e^{\varepsilon_{jt}}, \tag{1}$$

where Y is the value added, L denotes labour, K_P is the physical capital and K_R is the R&D capital.

Table 2 shows previous studies on the rate of return on R&D capital, estimated using production function. In summary, the majority of previous studies that estimate the rate of return on R&D capital find the rate to be quite high, typically over 20% (Hall *et al.* 2010). Table 3 shows previous studies on the rate of return on physical capital. Compared with the returns on R&D capital, those on physical capital are somewhat lower (Bernstein 1989).

[4] This study complements Branstetter and Nakamura (2003), who report the decline in R&D productivity of Japanese manufacturing firms after 1990 by using a patent counts function. The problem in estimating R&D productivity by this function lies in the fact that there are some R&D activities that are not patented. In addition, they estimate R&D productivity based on the data on patents granted to Japanese firms in the United States because of data availability. However, the number of patent applications by Japanese firms in the United States is little more than 20%.

[5] Low TFP growth was a key reason for the Japanese lost decade (Hayashi, Prescott 2002; Jorgenson, Nomura 2007). Branstetter and Nakamura (2003) show that R&D productivity of Japanese firms reached a plateau around 1990 and grew little thereafter. Japanese firms were thought to be effective imitators and implementers rather than innovators by 1990. Raising TFP and advancing technological frontier are the necessary conditions for firms in R&D-intensive industries to raise the rate of return on R&D capital and get favorable performance.

Table 2. Previous studies on the rate of return on R&D capital

Author	Period	Sample	Method	R&D rate of return
Goto and Suzuki (1989)	1976–1984	Japan 40 firms	Ordinary Least Squares (OLS)	Electric 22–53%, Auto 25–33% Pharmaceutical 23–42%
Bernstein (1989)	1963–1983	Canada 9 industries	OLS/Translog	Chemical 25%, Electric 38%,
Griliches and Mairesse (1991)	1973–1980	Japan 406 firms U.S. 525 firms	OLS	Japan 20–56%, U.S. 25–41%
Hall and Mairesse (1995)	1980–1987	France 197 firms	Fixed effect (FE)	22%–34%
Bond *et al.* (2003)	1988–1996	Germany 234 firms U.K.239 firms	OLS, FE, system Generalised Method of Moments (GMM)	Germany 19%, U.K. 38% (system GMM)
Griffith *et al.* (2006)	1990–2000	U.K. 188 firms	OLS, system GMM, Olley and Pakes (OP)	14% (system GMM), 9% (OP)
Doraszelski and Jaumandreu (2013)	1991–1999	Spain 1,800 firms	OP	Chemical 35%, Metal 66%, Transport machinery 48%
Ortega-Argiles *et al*. (2015)	1990–2008	1,809 firms (U.S. 1,170, EU 639)	OLS FE, RE	High-tech manufacturing: 7–24% (*) Other manufacturing: 11–32%

Table 3. Previous studies on the rate of return on physical capital

Author	Period	Sample	Method	Physical capital rate of return
Bernstein (1989)	1963–1983	Canada 9 industries	OLS/Translog	Chemical 10%, Electric and electronics 11%
Brynjolfsson and Hitt (1996)	1987–1991	U.S. 380 firms	OLS	6%
Griffith *et al.* (2006)	1990–2000	U.K. 188 firms	OLS System GMM, OP	25% (sys GMM), 22% (OP)
Caselli and Feyrer (2007)	1950–2000	168 countries (Penn World Tables 6.1)	Growth accounting	U.S. 12%, U.K. 12%, France 9%, Japan 9%
Doraszelski and Jaumandreu (2013)	1991–1999	Spain 1,800 firms	OP	7–31%
Ortega-Argiles *et al*. (2015)	1990–2008	1,809 firms (U.S.1,170, EU639)	OLS FE, RE	High-tech manufacturing: 13–17% (*) Other manufacturing: 6–8%

Note: (*) Computed using R&D elasticity and means of the variables.

2. Methods to estimate the rate of return on capital

System generalised method of moments (GMM) by Blundell and Bond (1998) and the controlling functions methods proposed by Olley and Pakes (1996) (OP) and Ackerberg *et al.* (2015) (ACF) are representative production function approaches to deal with simultaneity issues[6]. Each approach is based on different assumptions and has different strengths and weaknesses (Griffith *et al.* 2006). Therefore, comparing the results using alternative approaches would be a constructive exercise.

First, a production function with R&D capital in log form is considered, where y is the value added, l denotes labour, k_P is the physical capital, and k_R is the R&D capital:

$$y_{jt} = a + \beta_L l_{jt} + \beta_P k_{P,jt} + \beta_R k_{R,jt} + \varepsilon_{jt}. \tag{2}$$

2.1. System GMM

Error term ε_{jt} is divided into three, η_j is an unobservable firm-specific component, and ψ_{jt} is a serially correlated unobservable productivity that follows $\psi_{jt} = \mu\psi_{jt-1} + e_{jt}$. The innovation in ψ_{jt} between t–1 and t, e_{jt} is uncorrelated with all the input choices prior to t. Furthermore, m_{jt} is a residual productivity shock, and is assumed *i.i.d.* over time and uncorrelated with l_{jt}, $k_{P,jt}$, and $k_{R,jt}$ for all t:

$$y_{jt} = a + \beta_L l_{jt} + \beta_P k_{P,jt} + \beta_R k_{R,jt} + \eta_j + \psi_{jt} + m_{jt}. \tag{3}$$

System GMM is applied to Equation (4), which is a dynamic representation of Equation (3), and then the minimum distance estimator is used to obtain β_L, β_P, and β_R:

$$\begin{aligned} y_{jt} = {} & \beta_L l_{jt} - \mu\beta_L l_{jt-1} + \beta_P k_{P,jt} - \mu\beta_P k_{P,jt-1} + \beta_R k_{R,jt} - \mu\beta_R k_{R,jt-1} + \mu\, q_{jt-1} + \\ & a(1-\mu) + \eta_j(1-\mu) + e_{jt} + m_{jt} - \mu m_{jt-1}. \end{aligned} \tag{4}$$

2.2. ACF procedure[7] with R&D capital

The essence of ACF is to address simultaneity and selection problems using a function that controls for unobserved productivity. ACF improves the OP procedure by assuming labour to be a dynamic input and by solving collinearity problems. The original ACF procedure is modified by adding R&D capital. The error term is divided into $\varepsilon_{jt} = \omega_{jt} + \nu_{jt}$. Both ω_{jt} and ν_{jt} are unobserved, but only ω_{jt} is a state variable in the firm's decision problem.

Labour is assumed to have dynamic implications[8] in that the labour choices at period t would affect the firms' optimal choices afterwards. In this approach, $k_{P,jt}, k_{R,jt}, \omega_{jt}$ and

[6] Griffith *et al.* (2006) is one of the few studies that measures the rate of return on R&D capital using various methods: OLS, system GMM and OP.

[7] The ACF procedure has been applied in recent analyses (Greenstone *et al.* 2010; Brandt *et al.* 2012). This paper is novel in that it applies ACF procedures with R&D capital.

[8] OP assumes that labour is a non-dynamic input. Where there is significant hiring or firing costs for labour, where labour contracts are long-term, or where it takes a long time to train employees, the current labour input choices have dynamic implications.

l_{jt} are included in the investment function. Furthermore, a firm's optimal investment level is assumed to be a strictly increasing function of the firm's current productivity, ω_{jt}:

$$i_{jt} = i\left(k_{P,jt}, k_{R,jt}, l_{jt}, \omega_{jt}\right). \tag{5}$$

Assuming that there is strict monotonicity of the investment function in ω_{jt} and that ω_{jt} is the only unobservable term in the investment function, i_{jt} can be inverted to obtain ω_{jt}[9]:

$$\omega_{jt} = \tilde{\omega}_{jt}\left(i_{jt}, k_{P,jt}, k_{R,jt}, l_{jt}\right). \tag{6}$$

In the first-stage estimation, a third-order polynomial of $\left(i_{jt}, k_{P,jt}, k_{R,jt}, l_{jt}\right)$ is used for $\tilde{\omega}$, and $\hat{\varphi}_{jt}$ is obtained[10]:

$$\begin{aligned} y_{jt} = a + \beta_L l_{jt} + \beta_P k_{P,jt} + \beta_R k_{R,jt} + \tilde{\omega}_{jt}\left(i_{jt}, k_{P,jt}, k_{R,jt}, l_{jt}\right) + \nu_{jt} \equiv \\ \phi_{jt}\left(i_{jt}, k_{P,jt}, k_{R,jt}, l_{jt}\right) + \nu_{jt}. \end{aligned} \tag{7}$$

The following shows the optimal exit decision rule, where $\bar{\omega}_{jt}$ is the threshold level for the states below, in which a firm exits:

$$\chi_{jt} = \begin{cases} 1 & \text{if } \omega_{jt} \geq \bar{\omega}_{jt}, \\ 0 & \text{otherwise.} \end{cases} \tag{8}$$

In the second-stage estimation, the survival probabilities P_{jt} are obtained using a probit model:

$$\begin{aligned} \Pr\left\{\chi_{jt} = 1 \middle| \bar{\omega}_{jt}, J_{jt-1}\right\} = \Pr\left\{\omega_{jt} \geq \bar{\omega}_{jt} \middle| \bar{\omega}_{jt}, \omega_{jt-1}\right\} = \\ f\left\{\bar{\omega}_{jt}, \omega_{jt-1}\right\} = f\left(i_{jt-1}, k_{P,jt-1}, k_{R,jt-1}, l_{jt-1}\right) \equiv P_{jt}. \end{aligned} \tag{9}$$

By taking the expectation of ω_{jt} (conditional on the information set at t–1, J_{jt-1}) and setting $\bar{\omega}_{jt} = h\left(\omega_{jt-1}, P_{jt}\right)$ by Equation (9), the following equations are obtained:

$$\omega_{jt} = E\left[\omega_{jt} \middle| J_{jt-1}, \chi_{jt} = 1\right] + \xi_{jt} = E\left[\omega_{jt} \middle| J_{jt-1}, \omega_{jt} \geq \bar{\omega}_{jt}\right] + \xi_{jt} =$$

$$\int_{\bar{\omega}_{jt}}^{\infty} \omega_{jt} \frac{p\left(\omega_{jt} \mid \omega_{jt-1}\right) d\omega_{jt}}{\int_{\bar{\omega}_{jt}}^{\infty} p\left(\omega_{jt} \mid \omega_{jt-1}\right) d\omega_{jt}} + \xi_{jt} = g\left(\omega_{jt-1}, \bar{\omega}_{jt}\right) + \xi_{jt} =$$

$$g\left(\omega_{jt-1}, h\left(\omega_{jt-1}, P_{jt}\right)\right) + \xi_{jt} = g\left(\hat{\phi}_{jt-1} - a - \beta_L l_{jt-1} - \beta_P k_{P,jt-1} - \beta_R k_{R,jt-1},\ \hat{P}_{jt}\right) + \xi_{jt}. \tag{10}$$

(10)[11]

[9] Ackerberg *et al.* (2015) also propose an idea of using intermediate input demand function, suggested in Levinsohn and Petrin (2003), instead of using investment function.

[10] Year dummies are added in estimating Equation (7).

[11] Here, ω_{jt} follows a first-order Markov process, and ξ_{jt} is the unexpected innovation.

In the third-stage, considering the selection correction and using Equation (10), Equation (11) is obtained:

$$\begin{aligned} y_{jt} &= a + \beta_L l_{jt} + \beta_P k_{P,jt} + \beta_R k_{R,jt} + \\ & g\left(\hat{\phi}_{jt-1} - a - \beta_L l_{jt-1} - \beta_P k_{P,jt-1} - \beta_R k_{R,jt-1},\ \hat{P}_{jt}\right) + \xi_{jt} + \nu_{jt}. \end{aligned} \tag{11}$$

Then, polynomials are used to approximate g (•), and Equation (11) is estimated using nonlinear least squares. Thus, consistent estimates of β_L, β_P, and β_R are obtained.

2.3. Comparison of estimation methods: merits and disadvantages

2.3.1. System GMM

System GMM does not require the setting of strict monotonicity for the investment function in ω_{jt} as is required by control function methods such as the ACF approach. Furthermore, it is possible to estimate the coefficient even when the adjustment cost of investment is not negligible. However, system GMM suffers from a weak instruments problem when the variances in individual heterogeneity are large (Bun, Windmeijer 2010). In addition, it is necessary to pass the Sargan test of overidentifying restrictions to confirm instrumental validity.

2.3.2. ACF approach

The ACF approach can solve the simultaneity and selection problems inherent in production function estimations based on a structural model. However, there are two main problems in the ACF approach. First, it is assumed that the investment function at t is strictly monotonic in ω_{jt}. If the adjustment cost is not negligible, then the assumption of strict monotonicity will not be allowed, and Equation (6) will not hold. Second, when the investment is liquidity constrained, it will depend on cash flow (Brown *et al.* 2012). In such a case, the control function in Equation (6) will only capture part of the real productivity shocks.

3. Results and discussion

The rate of return on capitals was estimated using the methods introduced in sections 2.1 and 2.2[12] for three periods: the bubble period (1986–1990), the lost decade (1991–2001) and the period after the lost decade (2002–2010), along with the whole sample period. By definition, the rate of return on R&D capital is $\partial Y/\partial K_R = \beta_R \left(Y/K_R\right)$, and on physical capital it is $\partial Y/\partial K_P = \beta_P \left(Y/K_P\right)$. The results are shown in Tables 4–7[13]. The results from both methods, system GMM and ACF, are essentially similar, which reveals the estimation results to be robust. Because the trends of declining value added coincide with that of the declining rate of return on R&D capital for R&D-intensive industries, it is inferred that they have a strong correlation.

[12] Estimation results using the OP approach and OLS are also shown in Tables 4–7 as references.

[13] Sargan overidentification tests do not reject instrumental validity for all the estimations results by system GMM. Basically, the results of Arellano–Bond AR(2) test also do not reject the null hypothesis that a serial correlation exists. Only one exception is the estimation on machinery firms in the lost decade (Table 7), where the null hypothesis cannot be rejected at the 10% significance level.

3.1. Variables and data

Physical capital is calculated as $K_{P,jt+1} = \left(1 - \delta_P\right) K_{P,jt} + I_{jt}$ where I_{jt} is the investment. The depreciation rate of physical capital, δ_P, is calculated applying Hayashi and Inoue (1991). Furthermore, L is the number of employees, K_R is calculated as $K_{Rt+1} = \left(1 - \delta_R\right) K_{Rt} + R_t$, where R is the R&D expenditure and δ_R is its depreciation rate[14] of R&D capital. All the variables are in real terms, and Y[15], I and R are calculated using the financial statements of listed firms, which were obtained from NEEDS-Financial QUEST for the fiscal years 1986–2010. The sample, which satisfies all the necessary variables, includes 54 pharmaceutical firms, 255 electric and electronic manufacturing firms, 187 chemical firms and 329 machinery firms.

3.2. Results: rate of return on physical capital and R&D capital

3.2.1. Pharmaceutical firms

Table 4 shows the results for pharmaceutical firms. The rates of return on both capitals are the highest among the R&D-intensive industries for whole sample period. In the bubble period, 1986–1990, the rates of return on both capitals were quite high, and remained so during the lost decade, 1991–2001. However, in the period 2002–2010, the rate on R&D capital declined significantly[16].

3.2.2. Electric and electronic manufacturing firms

Table 5 shows that the rates of return on both capitals for the whole sample period are at similar levels. In the bubble period, the rate of return on R&D capital was much higher compared with that of physical capital. However, the rate of return on R&D capital substantially declined in the lost decade. After 2002, the rate of return on R&D capital recorded negative growth, while the rate on physical capital remained rather stable.

3.2.3. Chemical firms

The rate of return on R&D capital is lower than that on physical capital for whole sample period. The rate of return on R&D capital was much higher than that of physical capital in the bubble period. However, the rate of return on R&D capital declined significantly after that period, while the rate of return on physical capital reveals an upward trend (Table 6).

[14] Depreciation rates for R&D capital by sectoral basis estimated by Sakai (2016) are used in this paper: 20.9% for pharmaceutical firms, 29.3% for electronic firms, 21.6% for chemical firms and 19.5% for machinery firms.

[15] Value added is calculated by net operating income + depreciation + salaries and wages + rental or leasing expenses for fixed and liquid assets + taxes and public charges, using financial statements of each firm.

[16] Scherer (2010) points out that the probability of success in developing drugs has become lower in recent years.

Table 4. Comparison of results from the four estimation methods for pharmaceutical firms

Whole sample, 1986-2010	System GMM		ACF		OP		OLS	
	Coef.	Std. errors	Coef.	Std. errors	Coef.	Std. errors	Coef.	Std. errors
β*L*	0.25	0.20	0.72	0.04 ***	0.69	0.05 ***	0.86	0.04 ***
β*P*	0.21	0.07 ***	0.13	0.02 **	0.06	0.08	0.21	0.03 ***
β*R*	0.26	0.07 ***	0.18	0.03 ***	0.13	0.06 **	0.12	0.02 ***
Sargan	1.00							
AR(1) p-value	0.03							
AR(2) p-value	0.72							
Adjusted R squared			0.92		0.66		0.90	
Number of firms	53		51		51		54	
Samples	1,052		780		780		1,077	
Rate of return on physical capital	23.6%		12.1%		5.8%		23.5%	
Rate of return on R&D capital	19.5%		14.4%		10.6%		9.0%	
Sub samples								
1. 1986–1990	Coef.	Std. errors	Coef.	Std. errors	Coef.	Std. errors	Coef.	Std. errors
β*L*	0.19	0.06 ***	0.30	0.26	0.62	0.13 ***	0.90	0.12 ***
β*P*	0.25	0.01 ***	0.20	0.12 *	0.06	0.05	0.08	0.08
β*R*	0.26	3.E-03 ***	0.22	0.07 ***	0.18	0.03 ***	0.17	0.05 ***
Sargan	1.00							
AR(1) p-value	0.19							
AR(2) p-value	0.12							
Adjusted R squared			0.97		0.62		0.88	
Number of firms	38		35		35		42	
Samples	184		159		159		189	
Rate of return on physical capital	24.5%		17.9%		5.0%		8.1%	
Rate of return on R&D capital	28.2%		25.4%		21.1%		18.3%	
2. 1991–2001	Coef.	Std. errors	Coef.	Std. errors	Coef.	Std. errors	Coef.	Std. errors
β*L*	0.27	0.05 ***	0.26	0.21	0.60	0.07 ***	0.73	0.06 ***
β*P*	0.26	0.04 ***	0.17	0.12	0.14	0.12	0.29	0.04 ***
β*R*	0.39	0.11 ***	0.28	0.09 ***	0.20	0.09 **	0.11	0.02 ***
Sargan	1.00							
AR(1) p-value	0.02							
AR(2) p-value	0.49							
Adjusted R squared			0.934		0.797		0.917	
Number of firms	48		45		45		48	
Samples	495		381		381		505	
Rate of return on physical capital	25.8%		15.6%		12.9%		28.0%	
Rate of return on R&D capital	31.9%		23.2%		17.1%		8.8%	
3. 2002–2010	Coef.	Std. errors	Coef.	Std. errors	Coef.	Std. errors	Coef.	Std. errors
β*L*	0.45	0.04 ***	0.85	0.19 ***	0.87	0.08 ***	0.93	0.08 ***
β*P*	0.17	0.04 ***	0.11	0.12	0.16	0.08 **	0.18	0.06 ***
β*R*	0.08	0.01 ***	0.12	0.09	0.06	0.04	0.14	0.04 ***
Sargan	0.17							
AR(1) p-value	0.00							
AR(2) p-value	0.58							
Adjusted R squared			0.98		0.49		0.89	
Number of firms	52		44		44		53	
Samples	373		240		240		383	
Rate of return on physical capital	23.1%		11.7%		16.8%		24.1%	
Rate of return on R&D capital	5.0%		7.9%		3.8%		9.1%	

Notes: ***, ** and * indicate significance at the 0.01, 0.05 and 0.1 levels, respectively. The same conventions are used hereafter.
The set of instruments for the system GMM estimator contains *y, l, kp* and *kr* lagged two periods or more in the difference equation and first difference of *y* dated *t*-1 in the level equation (Eq. (4)). The same cohnventions are used hereafter.

Table 5. Comparison of results from the four estimation methods for electric and electronic firms

Whole sample, 1986–2010	System GMM		ACF		OP		OLS	
	Coef.	Std. errors	Coef.	Std. errors	Coef.	Std. errors	Coef.	Std. errors
β*L*	0.33	0.01 ***	0.80	0.04 ***	0.82	0.01 ***	0.95	0.01 ***
β*P*	0.17	2.E-03 ***	0.14	0.02 ***	0.06	0.02 ***	0.07	0.01 ***
β*R*	0.07	1.E-03 ***	0.03	0.01 ***	0.05	0.01 ***	0.02	4.E-03 ***
Sargan	1.00							
AR(1) p-value	0.00							
AR(2) p-value	0.10							
Adjusted R squared			0.93		0.70		0.93	
Number of firms	253		241		241		255	
Samples	4,375		3,449		3,449		4,590	
Rate of return on physical capital	8.4%		6.3%		2.5%		3.5%	
Rate of return on R&D capital	9.8%		5.1%		8.4%		2.6%	
Sub samples								
1. 1986–1990	Coef.	Std. errors	Coef.	Std. errors	Coef.	Std. errors	Coef.	Std. errors
β*L*	0.24	0.01 ***	0.75	0.07 ***	0.78	0.03 ***	0.87	0.03 ***
β*P*	0.09	0.01 ***	0.13	0.05 ***	0.12	0.03 ***	0.07	0.02 ***
β*R*	0.08	2.E-03 ***	0.06	0.02 ***	0.04	0.02 **	0.04	0.01 ***
Sargan	0.37							
AR(1) p-value	0.01							
AR(2) p-value	0.83							
Adjusted R squared			0.96		0.66		0.96	
Number of firms	147		147		147		151	
Samples	630		597		597		704	
Rate of return on physical capital	4.6%		6.0%		5.2%		3.7%	
Rate of return on R&D capital	19.7%		16.7%		11.4%		9.9%	
2. 1991–2001	Coef.	Std. errors	Coef.	Std. errors	Coef.	Std. errors	Coef.	Std. errors
β*L*	0.38	0.01 ***	0.86	0.06 ***	0.84	0.02 ***	0.95	0.02 ***
β*P*	0.14	0.01 ***	0.14	0.05 ***	0.12	0.02 ***	0.06	0.01 ***
β*R*	0.04	2.E-04 ***	0.04	0.02 *	0.03	0.01 **	0.03	0.01 ***
Sargan	0.15							
AR(1) p-value	0.00							
AR(2) p-value	0.36							
Adjusted R squared			0.96		0.60		0.95	
Number of firms	213		208		208		226	
Samples	1,935		1,595		1,595		2,039	
Rate of return on physical capital	6.7%		5.9%		5.2%		4.3%	
Rate of return on R&D capital	5.6%		5.3%		4.4%		4.4%	
3. 2002–2010	Coef.	Std. errors	Coef.	Std. errors	Coef.	Std. errors	Coef.	Std. errors
β*L*	0.59	2.E-03 ***	0.93	0.05 ***	0.82	0.03 ***	1.04	0.02 ***
β*P*	0.25	2.E-03 ***	0.15	0.03 ***	0.22	0.02 ***	0.05	0.01 ***
β*R*	–0.02	1.E-04 ***	–0.02	0.02	–0.03	0.01 **	–2.E-03	0.01
Sargan	0.49							
AR(1) p-value	0.00							
AR(2) p-value	0.48							
Adjusted R squared			0.93		0.49		0.91	
Number of firms	233		208		208		234	
Samples	1,810		1,257		1,257		1,847	
Rate of return on physical capital	12.2%		6.8%		10.3%		2.7%	
Rate of return on R&D capital	–2.1%		–2.4%		–3.6%		–0.2%	

Table 6. Comparison of results from the four estimation methods for chemical firms

Whole sample, 1986–2010	System GMM		ACF		OP		OLS	
	Coef.	Std. errors	Coef.	Std. errors	Coef.	Std. errors	Coef.	Std. errors
β*L*	0.22	2.E-03 ***	0.76	0.03 ***	0.72	0.01 ***	0.76	0.01 ***
β*P*	0.10	1.E-03 ***	0.23	0.02 ***	0.27	0.02 ***	0.28	0.01 ***
β*R*	0.04	1.E-03 ***	0.05	0.01 ***	0.03	0.02 *	0.01	4.E-03 ***
Sargan	1.00							
AR(1) p-value	0.00							
AR(2) p-value	0.14							
Adjusted R squared			0.96		0.70		0.95	
Number of firms	183		184		184		187	
Samples	3,445		3,106		3,106		3,706	
Rate of return on physical capital	5.7%		12.4%		14.4%		16.1%	
Rate of return on R&D capital	4.0%		5.5%		3.6%		0.6%	
Sub samples								
1. 1986–1990	Coef.	Std. errors	Coef.	Std. errors	Coef.	Std. errors	Coef.	Std. errors
β*L*	0.19	0.02 ***	0.35	0.28	0.65	0.03 ***	0.69	0.02 ***
β*P*	0.07	0.02 ***	0.07	0.09	0.06	0.08	0.31	0.02 ***
β*R*	0.19	0.04 ***	0.11	0.05 **	0.08	0.04 *	0.01	0.01 **
Sargan	0.19							
AR(1) p-value	0.00							
AR(2) p-value	0.87							
Adjusted R squared			0.98		0.90		0.97	
Number of firms	104		110		110		125	
Samples	485		459		459		572	
Rate of return on physical capital	5.2%		4.9%		4.3%		24.1%	
Rate of return on R&D capital	38.8%		25.8%		18.4%		3.0%	
2. 1991–2001	Coef.	Std. errors	Coef.	Std. errors	Coef.	Std. errors	Coef.	Std. errors
β*L*	0.21	3.E-03 ***	0.73	0.05 ***	0.77	0.02 ***	0.81	0.01 ***
β*P*	0.14	2.E-03 ***	0.23	0.04 ***	0.18	0.02 ***	0.22	0.01 ***
β*R*	0.04	1.E-04 ***	0.04	0.02 **	0.04	0.01 ***	0.00	4.E-03
Sargan	0.39							
AR(1) p-value	0.00							
AR(2) p-value	0.71							
Adjusted R squared			0.97		0.78		0.96	
Number of firms	148		145		145		168	
Samples	1,456		1,379		1,379		1,609	
Rate of return on physical capital	8.2%		12.5%		10.1%		13.5%	
Rate of return on R&D capital	4.0%		4.2%		4.6%		0.2%	
3. 2002–2010	Coef.	Std. errors	Coef.	Std. errors	Coef.	Std. errors	Coef.	Std. errors
β*L*	0.21	1.E-03 ***	0.73	0.07 ***	0.78	0.02 ***	0.72	0.02 ***
β*P*	0.22	2.E-03 ***	0.30	0.05 ***	0.20	0.02 ***	0.35	0.02 ***
β*R*	0.03	2.E-03 ***	0.01	0.03	–3.E-04	4.E-04	0.01	0.01
Sargan	0.71							
AR(1) p-value	0.00							
AR(2) p-value	0.58							
Adjusted R squared			0.94		0.70		0.94	
Number of firms	182		179		179		182	
Samples	1,504		1,268		1,268		1,525	
Rate of return on physical capital	10.1%		13.7%		8.9%		15.8%	
Rate of return on R&D capital	2.3%		1.3%		0.0%		1.0%	

3.2.4. Machinery firms

Table 7 shows that the rate of return on R&D capital is much lower than that on physical capital for whole sample period. In the bubble period, the rate of return on both capitals was high. After the lost decade, the rate on R&D capital dropped significantly. After 2002, while the rate on both the capitals declined, the rate of return on physical capital remained rather stable.

3.3. Results: total factor productivity (TFP)

The log of TFP can be derived by subtracting the inputs $(\beta_L l_{jt} + \beta_P k_{P,jt} + \beta_R k_{R,jt})$ from the left side of Equation (2). Table 8 shows the estimation results of TFP by industries for three periods using the results of the estimated parameter by system GMM and ACF.

The estimated TFP growth by both methods shows similar trends. The results show a slowdown in the growth of TFP after 1991 except for pharmaceutical firms, which reveal declining TFP growth after 2002; this coincides with the estimated trend of the rate of return on R&D capital.

Table 8. Average growth of TFP by industries

		1986–1990	1991–2001	2002–2010
Pharmaceutical	system GMM	1.6%	1.9%	0.5%
	ACF	4.0%	2.8%	1.8%
Electric and Electronic	system GMM	8.0%	2.2%	0.1%
	ACF	9.0%	4.0%	0.4%
Chemical	system GMM	2.6%	–1.4%	–1.7%
	ACF	1.4%	0.9%	–1.2%
Machinery	system GMM	6.4%	–2.0%	–0.1%
	ACF	7.7%	–0.3%	0.5%

3.4. Discussion

The rate of return on R&D and physical capital, and TFP are estimated to identify the causes for the recent decline in the performance of R&D-intensive industries in Japan. After Japan entered the lost decade, the rate of return on R&D capital dropped significantly, while the rate on physical capital did not. These results contradict previous studies that show a high rate of return on R&D capital. Compared with the results of the recent study by Ortega-Argiles *et al.* (2015)[17], the rate of return on R&D capital is much lower for R&D-intensive firms in Japan than high-tech firms in the United States and the European Union. This suggests that there are factors particular to Japan.

[17] Ortega-Argiles *et al.* (2015), which use US and EU firms over the period 1990–2008, show that the rate of return on R&D capital is higher for low-tech sectors than for high-tech sectors.

Table 7. Comparison of results from the four estimation methods for machinery firms

Whole sample, 1986–2010	System GMM			ACF			OP			OLS		
	Coef.	Std. errors		Coef.	Std. errors		Coef.	Std. errors		Coef.	Std. errors	
β*L*	0.24	2.E-03	***	0.85	0.05	***	0.80	0.01	***	0.84	0.01	***
β*P*	0.16	1.E-03	***	0.21	0.04	***	0.20	0.02	***	0.16	0.01	***
β*R*	0.01	5.E-06	***	0.01	0.01		0.02	0.01	*	0.03	3.E-03	***
Sargan	0.26											
AR(1) p-value	0.00											
AR(2) p-value	0.81											
Adjusted R squared				0.93			0.51			0.91		
Number of firms	328			318			318			329		
Samples	5,579			4,477			4,477			5,909		
Rate of return on physical capital	10.3%			13.9%			13.2%			10.5%		
Rate of return on R&D capital	1.4%			2.9%			3.1%			6.1%		
Sub samples												
1. 1986–1990	Coef.	Std. errors		Coef.	Std. errors		Coef.	Std. errors		Coef.	Std. errors	
β*L*	0.43	0.09	***	0.82	0.04	***	0.70	0.03	***	0.72	0.03	***
β*P*	0.10	0.03	***	0.19	0.03	***	0.27	0.02	***	0.23	0.02	***
β*R*	0.03	2.E-03	***	0.03	0.01	**	0.03	0.01	***	0.02	0.01	**
Sargan	0.10											
AR(1) p-value	0.02											
AR(2) p-value	0.34											
Adjusted R squared				0.94			0.74			0.94		
Number of firms	166			174			174			183		
Samples	737			695			695			823		
Rate of return on physical capital	8.7%			16.3%			23.4%			19.3%		
Rate of return on R&D capital	12.8%			13.5%			14.7%			8.8%		
2. 1991–2001	Coef.	Std. errors		Coef.	Std. errors		Coef.	Std. errors		Coef.	Std. errors	
β*L*	1.05	0.02	***	0.83	0.05	***	0.81	0.02	***	0.90	0.02	***
β*P*	0.21	0.01	***	0.16	0.04	***	0.15	0.02	***	0.13	0.02	***
β*R*	0.01	6.E-05	***	0.01	0.01		0.03	0.01	***	0.02	0.01	***
Sargan	0.12											
AR(1) p-value	0.00											
AR(2) p-value	0.05											
Adjusted R squared				0.92			0.42			0.92		
Number of firms	262			258			258			289		
Samples	2,392			1,937			1,937			2,506		
Rate of return on physical capital	13.8%			10.9%			10.0%			8.4%		
Rate of return on R&D capital	1.7%			2.4%			8.9%			5.1%		
3. 2002–2010	Coef.	Std. errors		Coef.	Std. errors		Coef.	Std. errors		Coef.	Std. errors	
β*L*	0.26	0.01	***	0.92	0.04	***	0.80	0.02	***	0.84	0.02	***
β*P*	0.07	0.01	***	0.15	0.03	***	0.22	0.01	***	0.16	0.01	***
β*R*	2.E-03	6.E-06	***	2.E-03	0.01		0.01	0.01		0.03	0.01	***
Sargan	0.12											
AR(1) p-value	0.00											
AR(2) p-value	0.49											
Adjusted R squared				0.92			0.44			0.90		
Number of firms	309			293			293			314		
Samples	2,450			1,845			1,845			2,580		
Rate of return on physical capital	4.1%			9.1%			13.1%			9.7%		
Rate of return on R&D capital	0.3%			0.3%			1.0%			5.6%		

A declining rate of return on R&D capital, the slowdown of TFP growth,[18] and the declining average growth of value added occur coincidentally for all R&D-intensive industries. Judging from the coincidence of these trends, the declining rate of return on R&D capital along with the slowdown of TFP growth are the main causes of the recent low performance of R&D-intensive industries. Furthermore, it is suggested that innovations that enable the effective use of R&D capital are stagnating.

Possible reasons for this decline and the slowdown are as follows. First, Japanese firms fall far behind those in other countries in terms of opening up their R&D strategies and coordinating their technology seeds to other firms, universities and the government[19]. In this sense, knowledge spillover is not fully exploited. Second, the development of complementary factors of R&D capital such as human capital[20] and management practices[21] is given low priority. It is necessary to develop those complementary factors to use R&D capital effectively. Third, the liquidity constraint problem[22] may have curbed R&D investments in new businesses, thereby discouraging innovation and causing a drop in productivity. Additional quantitative analyses are necessary to test these hypotheses.

Conclusions

This study measured the rate of return on R&D and physical capital, and the TFP of Japanese firms in R&D-intensive industries. The rate of return on R&D capital and TFP growth dropped significantly after Japan entered the lost decade, while the rate on physical capital did not. Because the declining rate of return on R&D capital and the slowdown of TFP growth occurred coincidentally with the stagnating growth of value added, it is suggested that they are the main causes of the recent low performance of R&D-intensive industries.

The main contributions of this paper can be summarized as follows. First, this study contributes to the existing literature in that it estimates the rate of return using recent data. As shown in Tables 2 and 3, very few studies have provided empirical evidence on a sectoral basis using data from after 2000. Second, we analysed the rate of return on capitals using models that deal with simultaneity bias, and found that our results contradict those in previous studies. Furthermore, this paper is novel in that it applies

[18] The result is consistent with that by Hayashi and Prescott (2002). Jorgenson and Nomura (2007) also demonstrate that the TFP growth of the Japanese manufacturing sector stalled during between 1990 and 2000, which is consistent with our findings in this paper. However, they also show that TFP began to revive from 2000 to 2004, which contradicts the results in our study.

[19] Branstetter and Sakakibara (2002) find strong evidence that spillover potential is positively related to the outcomes of consortia. Branstetter and Nakamura (2003) note that the Japanese firms embedded in US technology networks enjoy a relatively higher level of R&D productivity.

[20] Arora *et al.* (2013) find that Japanese IT firms had weaker innovation performance in the 1990s than those in the United States because of a limited supply of human resources with software knowledge and skills.

[21] New management techniques and management practices are also thought to be important complementarity factors of R&D capital (Dudley, Moenius 2007).

[22] As is shown in 2.3.2, the ACF approach will not work well under the liquidity constraint.

ACF procedures with R&D capital. The recent trend of a declining rate of return on R&D capital cannot be found using OLS, the method typically used in previous studies (Tables 4–7). System GMM and ACF procedures will become mainstream in production function analyses hereafter. Third, this study estimated TFP and found that its slowdown and the declining rate of return on R&D capital occurred coincidentally. The importance of innovations that enable effective use of R&D capital is also suggested in this paper. Fourth, the results of this paper offer suggestions on economic policies and growth strategies. Relying on the belief that the rate of return on R&D capital remains high, R&D tax cuts to promote R&D investment were implemented as part of the growth strategy under "Abenomics"[23] in Japan. According to the results of this paper, however, simply promoting R&D investment will be ineffective for growth. The factors behind the declining rate of return on R&D capital and methods to reverse this must be examined simultaneously.

This study has two limitations. First, we limited the sample to listed firms only, while some unlisted small and medium-sized firms are actively promoting R&D. Thus, it would be productive to enlarge the sample size to unlisted firms to better understand the recent situation concerning R&D-intensive industries. Second, this paper lacks qualitative evidence. Despite the declining rate of return on R&D capital, there are some Japanese firms in R&D-intensive industries (e.g., Keyence and Komatsu) that have sustained superior performance. Along with additional quantitative analyses, case studies of such firms are necessary to obtain clues as to how to revive the performance of firms that belong to R&D-intensive industries by implementing technology networks, human capital and management practices. These topics remain to be solved in future studies to complement the results of this paper.

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[23] "Abenomics" refers to the economic policies advocated by Shinzo Abe, Prime Minister of Japan, since the December 2012.

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APPENDIX

Descriptive statistics

1. Pharmaceutical firms

1986–1990	Mean	Std. dev.	Min.	Max.	Samples
Number of employees	2,260.3	2,166.8	78	10,946	189
Physical capital stock (one mil. yen)	21,378.5	26,173.7	1,101.0	156,626.0	189
R&D capital stock (one mil. yen)	16,414.0	21,029.4	80.6	120,821.6	189
Value added (one mil. yen)	18,870.4	20,878.1	529.3	100,365.6	189
1991–2001					
Number of employees	2,087.3	2,038.3	87	11,137	505
Physical capital stock (one mil. yen)	28,704.4	34,471.3	468.8	184,997.0	505
R&D capital stock (one mil. yen)	31,562.1	43,424.7	3.3	265,969.2	505
Value added (one mil. yen)	26,770.8	36,949.7	267.3	310,771.4	505
2002–2010					
Number of employees	1,687.7	1,620.2	39	6,471	383
Physical capital stock (one mil. yen)	29,317.8	36,242.2	93.9	300,629.0	383
R&D capital stock (one mil. yen)	49,231.1	83,259.5	63.0	668,593.8	383
Value added (one mil. yen)	34,735.1	60,227.3	6.4	424,863.8	383

2. Electric and electronic manufacturing firms

1986–1990	Mean	Std. dev.	Min.	Max.	Samples
Number of employees	4,212.2	11,023.0	36	79,801	704
Physical capital stock (one mil. yen)	43,015.1	120,016.2	230.8	930,259.0	704
R&D capital stock (one mil. yen)	7,665.6	30,598.9	0.6	297,812.8	704
Value added (one mil. yen)	19,995.5	55,938.6	156.9	468,293.5	704
1991–2001					
Number of employees	3,595.9	9.639.0	32	81,488	2,039
Physical capital stock (one mil. yen)	62,855.8	200,456.3	42.9	1,578,860.5	2,039
R&D capital stock (one mil. yen)	17,402.5	75,935.1	2.0	732,343.6	2,039
Value added (one mil. yen)	27,686.3	77,093.3	139.2	612,247.8	2,039
2002–2010					
Number of employees	2,384.3	5,909.3	12	42,375	1,847
Physical capital stock (one mil. yen)	69,600.7	232,687.1	3.8	1,722,944.5	1,847
R&D capital stock (one mil. yen)	25,294.5	102,305.7	2.0	819,679.4	1,847
Value added (one mil. yen)	31,956.7	90,058.8	12.2	795,304.3	1,847

3. Chemical firms

1986–1990	Mean	Std. dev.	Min.	Max.	Samples
Number of employees	1,759.4	2,350.3	68	15,566	572
Physical capital stock (one mil. yen)	33,538.5	53,615.9	290.2	364,591.0	572
R&D capital stock (one mil. yen)	9,531.4	22,507.1	10.0	210,977.0	572
Value added (one mil. yen)	22,854.9	36,106.4	877.7	272,319.9	572
1991–2001					
Number of employees	1,404.9	2,008.6	55	17,576	1,609
Physical capital stock (one mil. yen)	38,070.1	67,864.2	364.7	481,557.0	1,609
R&D capital stock (one mil. yen)	17,345.8	43,112.5	2.5	450,470.0	1,609
Value added (one mil. yen)	21,161.6	36,465.2	274.5	283,997.2	1,609
2002–2010					
Number of employees	932.2	1,185.0	30	11,659	1,529
Physical capital stock (one mil. yen)	34,101.7	62,560.2	36.1	534,756.0	1,529
R&D capital stock (one mil. yen)	16,143.2	41,109.3	0.9	466,997.0	1,529
Value added (one mil. yen)	15,526.2	25,354.9	22.7	224,865.8	1,529

4. Machinery firms

1986–1990	Mean	Std. dev.	Min.	Max.	Samples
Number of employees	2,351.9	4,597.3	56	47,488	823
Physical capital stock (one mil. yen)	23,087.6	49,063.6	252.9	500,706.0	823
R&D capital stock (one mil. yen)	4,591.7	15,757.4	0.7	140,848.2	823
Value added (one mil. yen)	20,165.2	42,013.3	697.5	573,854.1	823
1991–2001					
Number of employees	1,968.5	3,960.3	15	45,353	2,506
Physical capital stock (one mil. yen)	30,240.4	73,136.3	1.4	812,969.0	2,506
R&D capital stock (one mil. yen)	6,696.1	31,219.1	1.2	1,103,753.0	2,506
Value added (one mil. yen)	20,694.0	48,158.0	34.9	624,791.2	2,506
2002–2010					
Number of employees	1,509.5	3,101.1	13	35,530	2,580
Physical capital stock (one mil. yen)	32,327.3	82,719.9	1.2	875,300.0	2,580
R&D capital stock (one mil. yen)	14,462.2	111,197.6	0.1	2,322,699.0	2,580
Value added (one mil. yen)	19,466.4	45,485.4	57.3	611,696.9	2,580

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