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Prices, the military revolution, and western Europe's comparative advantage in violence[1]

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Price data from England, France, and Germany show that the military sector in western Europe experienced rapid and sustained productivity growth well before the industrial revolution. The productivity growth has implications for the history of the military revolution in early modern Europe and helps explain why western Europe gained a comparative advantage in violence. It also raises questions about the economic impact of the military revolution.

In recent years, historians, economists, and other social scientists have energetically debated when Western Europe first forged ahead of other parts of the world—in particular, advanced parts of Asia—in the race toward economic development. Was it only after 1800, with the industrial revolution well underway, that western European per-capita incomes, labour productivity, or technology diverged, or was it earlier, before the industrial revolution? What was the cause of the divergence? Was it beneficial institutions, which stimulated investment and the accumulation of human and physical capital; the evolution of cultural practices that encouraged hard work and education; the scientific revolution and the Enlightenment, which spread useful knowledge and political reform; or was it simply an accident that the industrial revolution started in western Europe?[2]

In this debate, one area in which western Europe possessed an undeniable comparative advantage well before 1800 seems to have been overlooked—namely, violence. The states of western Europe were simply better at making and using artillery, firearms, fortifications, and armed ships than other advanced parts of the world and they had developed the fiscal and organizational systems that armies and navies equipped with this technology required. The Europeans had this advantage long before 1800. By then, they had conquered some 35 per cent of the globe, and they controlled lucrative trade routes as far away as Asia.[3] Some of the

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[2] For the divergence debate, see Pomeranz, *Great divergence*; Wong, *China transformed*; Goldstone, *Rise*; van Zanden, 'Rich and poor'; Allen, 'Real wages in Europe and Asia'; Broadberry and Gupta, 'Early modern great divergence'. For arguments in favour of institutions, see North and Thomas, *Rise of the western world*; North and Weingast, 'Constitutions and commitment'; Acemoglu, Johnson, and Robinson, 'Reversal of fortune'. For the other explanations, see G. Clark, 'The great escape: the industrial revolution in theory and history', working paper, UC Davis Department of Economics (2003); idem, *Farewell to alms*; Mokyr, *Gifts of Athena*; Jacob, *Scientific culture*; Cosandey, *Le secret de l'Occident*.

[3] Parker, *Military revolution*, p. 5.

land they subjugated had come into their hands because of new diseases that they introduced into vulnerable populations, and in these instances—in the Americas in particular—their advantage was not military, but biological.[4] Nevertheless, other inhabitants of densely populated parts of Eurasia would have had the same biological edge. Why was it therefore the western Europeans who took over the Americas, and not the Chinese or the Japanese?

The history of conquest is not the only evidence for western Europe's military advantage before 1800. States elsewhere—China, Japan, and the Ottoman Empire—certainly possessed firearms or ships equipped with artillery, but by the late seventeenth century, if not before, nearly all of them had fallen behind in using this technology. The case of the Ottoman Empire is illustrative. There the military gap may reach back as far as 1572, when Venetian cannon founders judged that guns captured during the naval battle at Lepanto were simply not worth reusing. The Ottoman cannons had to be melted down, and new metal had to be added to the mixture, because 'the material is of such poor quality'.[5] At a time when the high cost of manufactured goods meant everything was salvaged—even clothing from fallen comrades—that amounts to strong evidence from revealed preference about how much better western European weapons had become. The history of trade and the migration of military experts points in the same direction. Although the Ottomans had a 'robust ordnance industry' and could threaten Vienna as late as 1683, they imported weapons from western Europe and often relied on the expertise of European military specialists.[6]

The Ottoman Empire was hardly exceptional. From the middle east to east Asia, experts from western Europe were hired throughout Asia to provide necessary help with gun making, tactics, and military organization. They ranged from renegade European gunfounders in the sixteenth century to Napoleonic officers in the early 1800s. In seventeenth-century China, even Jesuit missionaries were pressed into service to help the Chinese Emperor make better cannons. The evidence for western Europe's military prowess is so strong that it has even convinced some of the historians who argue against any divergence between western Europe and advanced areas of China before 1800. Although they would argue that western Europe was not wealthier or more developed than rich areas of China, they would acknowledge that its military technology was more advanced.[7]

The evidence is thus fairly clear, but it is nonetheless surprising that western Europe had come to dominate the technology of gunpowder weapons so early. Firearms and gunpowder, after all, had originated in China and spread throughout Eurasia. States outside western Europe possessed these revolutionary weapons and did become, at least for a while, proficient at manufacturing or exploiting the new military technology. The Ottomans, for instance, long made high-quality artillery—perhaps as late as the 1700s. The Japanese discovered, some 20 years earlier than western Europeans, the key tactical innovation (volley fire) that allowed infantry soldiers with slow loading muskets to maintain a nearly continu-

[4] Diamond, *Guns, germs, and steel*.
[5] Mallett and Hale, *Military organization*, p. 400.
[6] See Heywood, 'Activities'; idem, 'Notes'; Parry, 'Materials of war'; Inalcik, 'Socio-political effects'; Parker, *Military revolution*, pp. 87–9, 126–9, 73–5; Chase, *Firearms*, pp. 2, 97–8; Agoston, *Guns for the sultan*, pp. 10–12 (the source of the quotation about the ordnance industry), 193–4.
[7] Pomeranz, *Great divergence*, pp. 199–200; Wong, *China transformed*, pp. 89–90.

ous round of fire.[8] Yet by the late seventeenth century, if not before, Chinese, Japanese, and Ottoman military technology and tactics all lagged behind what could be found in western Europe.[9]

Why did these other powerful states fall behind? Apart from Cipolla's pioneering effort some 40 years ago, economic historians have not paid much attention to this question.[10] Western Europe's advances in military tactics and technology have certainly attracted a number of talented military historians and historians of technology, but their work ignores the economics, even though they acknowledge that the cost of weapons fell.[11] What happens if we examine the political economy of the military revolution and look in particular at prices of military goods? What do they tell us about western Europe's growing military strength?

The price data, it turns out, offer some novel insights into the debates military and technological historians have had over the nature of the military revolution. They also carry the startling implication that Europe's military sector could maintain productivity growth for centuries, a feat virtually unknown elsewhere in pre-industrial economies. The sustained productivity growth has important economic implications for the role that the military played—for better and for worse—in European economies. It also gives us a deeper understanding of why Europeans came to dominate gunpowder technology and why they—and not the Chinese, Japanese, or Ottomans—were the ones who ultimately conquered the world. To be sure, there was more to the European conquests than technological prowess. The ability to fund and manage military ventures played a significant role, as did historical accidents and the nature of the enemies confronting countries outside of Europe.[12] Improved military technology was thus part of a larger process, alongside better fiscal systems and military organization; focusing on the technology cannot mean believing that it alone accounts for Europe's rise to power. Yet it was nonetheless extremely important. It helped Europeans wage war in faraway places without sending armies abroad, and it made the military arguably the most dynamic sector of Europe's pre-industrial economy, provided we set aside (at least temporarily) all the harm that the fighting did.

I

Suppose that we confine ourselves to examining the cost of producing the new weapons that played a key role in the military revolution—artillery, handguns, and gunpowder. Again, there were other factors involved, but for the moment we will consider the technology alone. The question then is whether the cost curves for

[8] With volley fire, infantrymen were trained to line up in long rows. The first row would fire their muskets, and while they were reloading, the rows behind them would advance to the front and take their place on the firing line. For volley fire in Europe and Japan, see Parker, *Military revolution*, pp. 18–19, 140–1.

[9] Agoston, *Guns for the sultan*, pp. 10–12, 193–4, argues that the European technological superiority was minimal, at least until the late seventeenth century, but he does admit that it was 'European military experts who sold their expertise to the Ottomans and not vice versa' (p. 193).

[10] Cipolla, *Guns, sails and empires*.

[11] In his detailed study of gunpowder technology, for example, Hall focuses on the big breakthroughs and downplays all sorts of steady improvements in the late sixteenth and seventeenth centuries that would interest an economist. In Hall's words, these steady improvements 'made gunpowder and firearms cheaper, easier to produce, and still more readily available than ever before, but they did little or nothing to alter the basic characteristics of the guns themselves'; Hall, *Weapons and warfare*, p. 215.

[12] For a careful account of all the other forces that played into the European conquest, see Black, *War and the world*.

producing these new military goods were declining, once we take into account changes in other prices. If the cost curves were shifting down, then the production functions for the weapons were moving out, and total factor productivity was increasing.

This sort of exercise certainly has its limits and is probably biased against finding any productivity growth. To begin with, it is likely to underestimate the magnitude of the military revolution. Ideally, we should be measuring the cost of attaining a given level of military effectiveness, but we are instead simply gauging the cost of producing certain military products, and only doing that once the products are available for sale in sufficient numbers to leave a historical record. Restricting our attention to the products also leaves out tactical innovations, better training, and (as we have already mentioned) improvements in provisioning armies and navies and in raising money to pay for military operations. Moreover, by omitting advances in ship construction, seaborne strategy, and maritime forces' ability to fight around the globe and in bad weather, it glosses over most of naval warfare, where western Europe's comparative advantage was probably greatest. Similarly, waiting until prices appear in the historical records is likely to omit the initial gains in productivity from learning by doing when the weapons were first introduced, but before sales and cost estimates left much of a trace in the archives.

In an ideal world, we could put together a long, homogenous series of prices for artillery, handguns, gunpowder, and the relevant factors of production in countries across the world. Unfortunately, that is not possible, in large part because prices for military goods—guns in particular—are hard to come by.[13] However, we do at least have somewhat fragmentary price data from England, France, and (for a smaller number of observations) Germany.

What then do the price data for artillery, handguns, and gunpowder from these countries tell us? The prices, despite their limitations, can in fact tell us a great deal, provided four assumptions hold: first, each of these military goods was each produced by cost minimizing firms that were small relative to the size of their markets; second, entry into these product markets was open; third, markets for the factors of production were competitive; and fourth, that the firms had U-shaped short-run average cost curves.

These are not unreasonable assumptions for England, France, and Germany, at least for the period covered by our prices. Factor markets were competitive, and weapons production in these countries was, for the most part, in the hands of a large number of small-scale contractors and independent craftsmen. Furthermore, entry into the weapons business did seem to be open, at least in the long run. Craftsmen and contractors moved their production from city to city and even entered the business from other fields or migrated from country to country.[14]

[13] Although accounting records in Europe contain evidence about prices back into the late middle ages, there is not enough of it to construct homogenous, uninterrupted price series for weapons and gunpowder. The problems are similar for key factors of production such as iron, copper, and wood. In addition, it is almost impossible to find prices for all of these goods in exactly the same year.

[14] For evidence supporting these assumptions, see Tout, 'Firearms in England'. This discusses the case of cannon making in late medieval England, the period for which we have prices (1382–1439). For English cannon making later, in the sixteenth century, see Rodger's discussion of the manufacture of naval artillery in his *Safeguard of the sea*, pp. 213–15, 225–6, 233. For cannon manufacturing in France during the period covered by our prices (1463–1785), see Bonaparte and Favé, *Etudes*; Contamine, 'Les industries de guerre'; Dubled, 'L'artillerie royale française'; Gaier, 'Le commerce des armes'; Gandilhon, *La politique économique*, pp. 195–215;

While there were some signs of fleeting collusion or high prices in England and France when their rulers wanted to nurture the native arms industry, they seem to have been temporary, because major weapons buyers (this was true in particular of governments) would go elsewhere if they thought prices were high.[15]

One might still worry that guilds or long-term contracts might have violated these assumptions by creating monopolies or barriers to entry in the weapons industry. In 1631, for instance, Charles I granted English handgun makers a monopoly which required them to fix their prices.[16] The monopoly, if effective, would have limited entry, and if it later collapsed, prices of muskets and pistols might have declined over the period for which we have data (1620–78 for muskets, 1556–1706 for pistols) without any productivity growth at all, as monopoly profits evaporated. There is also reason to doubt the assumption about the small size of firms. At the end of Louis XIV's reign, the production of French military handguns was concentrated in centres such as Charleville and Saint Etienne, where entrepreneurs such as Maximilien Titon turned out some 600,000 flintlocks in the 1690s alone.[17]

Yet on closer inspection such worries seem overblown. In England, the handgun makers' monopoly was not effective, at least not initially. Muskets and pistols were easily imported, and village blacksmiths had no trouble making matchlocks, the most common muskets before the use of flintlocks spread in the middle of the seventeenth century. Imports were finally restricted in 1661–2, and the restrictions and skills needed to manufacture flintlocks might have made the gun makers' monopoly more effective in the late seventeenth century. But if so, then the prices of English handguns would simply be biased against finding productivity growth.[18] In France, handgun production remained in the hands of small-scale manufacturers, despite the importance of entrepreneurs such as Titon and centres such as Saint Etienne. Titon, it turns out, was actually a purchaser of guns, not a manufacturer, and he and the government's other suppliers bought the weapons from small-scale gun makers. In Saint Etienne itself, according to Diderot and

Peter, *L'artillerie*; Archives Nationales (hereafter AN), Paris, Marine D/3/34, 'Compte fonderie d'Indret'. For French muskets in the period of our prices (1475–1792), see Lenk, *Flintlock*; Blanchard, Contamine, Corvisier, Meyer, and Mollat du Jourdan, *Histoire militaire*, pp. 411–12; Diderot and d'Alembert, eds., *Encyclopédie*, s.v. 'Canon de fusil', vol. 2, pp. 615–17; and the collection of Old Regime laws in Jourdan, Isambert, and Decrusy, *Recueil général des anciennes lois françaises*, which contains no legislation restricting the manufacture of muskets or fusils. See Rathgen, *Das Geschütz*, for cannons and handguns in late medieval Germany and specifically Frankfurt, the source of our prices. There, although the cannon makers did belong to the guild of smiths, they practiced their craft as a free trade, moved about, and entered the field from a variety of different occupations, at least in the period of concern to us (1399–1431).

[15] Although the English Ordnance Board nurtured the iron gun founding industry in sixteenth-century England, the goal was lower prices for cannons. Similarly, French officials (as Peter, *L'artillerie*, pp. 41–2, shows) did detect occasional signs of collusion among cannon makers in a particular market, but their reaction was usually to see if prices were lower elsewhere. When in the late eighteenth century the French government sought to import English iron making technology for cannon production, it subsidized the cost of hiring an English expert (William Wilkinson) to help transfer the technology. However, the French government was also deeply concerned to minimize costs. It did not promise to buy any of the output, and if it did, it would only pay the lower of a fixed price and the lowest price demanded by other producers. The subsidized foundry ended up losing money at the price the government paid. See AN, Marine, D/3/34, 'Traité pour l'établissement de deux hauts fourneaux pres Montcenis', 1782.

[16] Malcolm, *Guns and violence*, p. 49.

[17] Blanchard et al., *Histoire militaire*, pp. 411–12.

[18] Held, *Age of firearms*, pp. 51, 86, 91–104; Lenk, *Flintlock*, p. 53; Malcolm, 'Charles II'; idem, 'Creation'; idem, *Guns and violence*, p. 49.

d'Alembert's eighteenth-century *Encyclopédie*, the handgun industry was composed of a 'multitude' of workers so large 'that it can hardly be estimated' and by an equally sizeable number of factories.[19] There were not just one or two large mills, and the small-scale producers moved in and out of Saint Etienne in search of the best sites for their workshops.

The assumptions—small-scale cost minimizing producers, open entry, and competitive factor markets—thus seem plausible, and the possible instances when they may fail to hold (early seventeenth-century England) will only bias the results against detecting productivity growth. Under these assumptions, it would have been difficult for weapons producers to collude, and free entry would have driven them to produce at minimum average cost. That would have been the outcome even if there had been a monopsonist buyer, such as the government (which in any case never happened, since there was always private demand for handguns and artillery in western Europe). The long-run industry supply curve would then be flat, and the price of producing the military goods would equal their marginal and average cost. We can then measure the rate of productivity growth by regressing the logarithm of the price p of the military good on the logarithms of the costs of the factors of production, with all costs and prices measured relative to the cost of one of the factors of production, such as skilled labour.[20] In other words,

$$ln(p/w_0) = a - bt + s_1 ln(w_1/w_0) + \ldots + s_n ln(w_n/w_0) + u \qquad (1)$$

where a is a constant, $b > 0$ is the rate of total factor productivity growth, u is an error term, w_0 is the skilled wage, and s_i and w_i are the factor shares and prices of factors of production other than labour.

Unfortunately, we can rarely run such a regression, because the grudging historical record yields few years blessed with prices both for the military good and for all the factors of production. However, we can at least calculate p/w_0 for a large number of years and compare it with long-run averages of the relative prices w_1/w_0 through w_n/w_0. If p/w_0, the relative price of military goods relative to skilled labour, falls more rapidly than the relative prices of the other factors of production, then we have evidence of total factor productivity growth in the military sector, and we can estimate how large the rate of productivity growth must have been.

One simple way to do that is to make an educated guess at the factor shares s_i which would leave only the regression coefficients a and b to be estimated. Indeed, if we regroup the terms s_i ln (w_i/w_0) on the left side of equation 1, we have

$$ln(p/w_0) - s_1 ln(w_1/w_0) - \ldots - s_n ln(w_n/w_0) = a - bt + u \qquad (2)$$

The term on the left side of the inequality sign is simply an index of the price of the military good p relative to the costs of the factors of production, where these

[19] Blanchard et al., *Histoire militaire*, pp. 411–12; Diderot and d'Alembert, eds., *Encyclopédie*, s.v. 'Canon de fusil', vol. 2, pp. 615–17 (quotation); Peaucelle, 'Du concept d'interchangeabilité'.

[20] There are some minor technical assumptions involved here as well; for details, see P. T. Hoffman, 'Why is it that Europeans ended up conquering the rest of the globe? Prices, the military revolution, and western Europe's comparative advantage in violence', global price and income history working paper 3, URL http://www.gpih.ucdavis.edu/files/Hoffman.pdf [accessed 11 March 2009], and more generally idem, *Growth*.

Table 1. *Estimated rates of total factor productivity growth from of an index of prices relative to the cost of the factors of production: English and French weapons*

		Assumed factor shares					*Estimated total factor productivity growth*
Weapon	*Initial–final dates*	*Skilled labour*	*Capital*	*Iron*	*Copper*	*Wood*	*(% per year/t-statistic)*
France							
Artillery	1463–1785	0.5	0.125	0.125	0.125	0.125	0.6/16.35
Muskets	1475–1792	0.5	0.167	0.167		0.167	0.1/0.96
England							
Artillery	1382–1439	0.5		0.25		0.25	1.4/5.37
Muskets	1620–78	0.5	0.167	0.167		0.167	0.6/2.48
Pistols	1556–1706	0.5	0.167	0.167		0.167	0.8/4.08

Notes: The estimates are based on regressions using equation (2); see the text for details. If lack of data excluded a factor from the regressions, no factor share is shown.
Sources: England: Beveridge, *Prices and wages* (prices of firewood); Clark, 'Cost of capital' (interest rates for artillery); G. Clark, 'The agricultural revolution and the industrial revolution: England, 1500–1912', working paper, University of California at Davis (hereafter UC Davis) Department of Economics (2002) (interest rates for muskets and pistols); Phelps Brown and Hopkins, 'Seven centuries', (building craftsmen's wages); Rogers, 'Military revolutions' (prices of artillery after 1388); Rogers and Rogers, *History of agriculture and prices* (prices of handguns, iron, and firewood); Tout, 'Firearms in England', (prices of artillery in 1382–8). France: AN, Marine D/3/34, 'Compte fonderie d'Indret' (artillery prices); d'Avenel, *Histoire économique* (artillery and musket prices); Guyot, 'Essai sur l'aisance' (prices of iron and fir planks); Levasseur, *Les prix* (mason's wages, copper prices, and iron prices); Nicollière-Teijeiro and Blanchard, *L'inventaire sommaire*, CC 93–5 (artillery prices); J. Bytherne, 'Livre de guerre', in Bibliothèque nationale (hereafter BN), Paris, fonds français 3,890 (artillery prices); BN, fonds français 2,068, 'Prothocolle pour servir d'avertissement' (artillery prices).

The price of capital in both England and France is a rental price equal to $(i + d)p$, where i is the interest rate, d is the depreciation rate (set equal to 10 per cent annually), and p is the sales price of the capital good, which is assumed to be proportional to the skilled wage. For France, wages (for masons) are 25-year averages, as are the prices of iron, copper, and wood. The iron prices are Levasseur's, which are less reliable than Guyot's but have fewer gaps. Guyot's iron prices (and his accompanying skilled wages) would have yielded a faster rate of productivity growth. For England, prices of iron (wrought iron) and firewood (fagots) are 25-year averages. The interest rates used in calculating the price of capital for English artillery come from Clark's figures for rent charges in 'Cost of capital'. His figures are 50-year averages, and I have interpolated between 1351–1400 and 1451–1500 since Clark has no data for 1401–50. Here and in subsequent tables, the French artillery include canons, couleuvrines, serpentines, and *pieces de canon*. I used only those prices for which d'Avenel had converted the prices to francs per kilogram in order to avoid problems with different units of weight. Part of the lower cost of French cannons resulted from a shift in the seventeenth century from bronze to cast iron, which only cost 25–33 per cent as much per kilogram. The iron cannons did have to be heavier because they were more likely to explode, but even with the greater weight they only cost between a third or two-thirds as much as the equivalent bronze artillery. See Cipolla, *Guns, sails and empires*, p. 66, for details. Muskets in France included arquebuses, fusils, and mousquets; if the context made it clear that the mousquets or arquebuses were large calibre, they were excluded. I also excluded French and English handguns that were made for ornament or collection. As explained in the text, flintlocks, which appeared in the late seventeenth century, represent a qualitative improvement. Because they are included in the table, the productivity growth rates for muskets are underestimates.

costs are calculated from long-term averages.[21] We can then regress this index on time to estimate the rate of total factor productivity growth b, and we can vary our assumptions about the factor shares to ensure that our results are not simply a result of our guesses about the shares.

We have run such a regression for artillery and for handguns in late medieval and early modern England and France (table 1). The table is limited to one set of

[21] The expression on the left of the equality sign is just:

$$ln(p/((w_0 \hat{} s_0)*(w_1 \hat{} s_1)*\ldots*(w_n \hat{} s_n)))$$

where $s_0 = 1 - (s_1 + \ldots + s_n)$ is the factor share of labour and the factor shares s_i (for $i > 1$) are positive numbers whose sum is less than 1. For the other assumptions involved, see Hoffman, 'Europeans' (see above, n. 20).

guesses for the shares, but other values led to virtually identical results.[22] Apart from the 0.1 per cent rate of change for French muskets, the estimated rates of total factor productivity growth are all over 0.6 per cent per year, and the figure reaches 1.4 per cent among artillery makers in late medieval England. These numbers are quite large for the pre-industrial world, where long-run productivity growth rates usually did not exceed 0.1 per cent per year, at least in sectors of the economy as large as the military.[23] There were admittedly some exceptions to this rule—English agriculture, for instance, which seems to have sustained long-term total factor productivity growth rates of 0.2–0.3 per cent per year—but in most of the pre-industrial economy, faster growth could simply not be sustained.[24] Even during the industrial revolution, total factor productivity growth in Britain seems to have hovered between 0.1 per cent per year and 0.35 per cent per year.[25] How could the defence industry do so well over such long periods of time, and in two economies—France and England—that for most of the years in the table were largely pre-industrial?

Another way of analysing the price data leads to the same results—comparing the price p of our military good with that of a civilian commodity which involved a comparable production process. If the civilian commodity was made with similar factors of production and similar factor shares, and if the same economic assumption held for it too (small firms, open entry, U-shaped short-run average cost curves, competitive factor markets, and a Cobb-Douglas production function), then equation 1 would apply to its price q too, and the logarithm of p/q would be:

$$ln(p/q) = c - dt + e_1 ln(w_1/w_0) + \ldots + e_n ln(w_n/w_0) + v \quad (3)$$

Here c is a constant, d is the rate of total factor productivity growth for the military good minus that for the non-military good, v is an error term, and the e_is are differences in the factor shares for the two goods. We can therefore regress $ln\ (p/q)$ on time and on the available factor costs $ln\ (w_i/w_0)$ for which we have long-run averages and come up with an estimate for d, the rate of total factor productivity growth for our military good less that for our non-military good. The estimate will be biased if some of the variables $ln\ (w_i/w_0)$ are omitted from the regression, but if the e_is are small, then the bias will be small too and may be either positive or negative.[26] If production of the non-military good does not experience any technical change, then d will be close to the rate of productivity growth b for the military good. If there is technical change in production of the military good, the

[22] In the table the labour factor share is 0.5 and the other shares are all equal. The total factor productivity estimates do not change by more than 0.1% per year if we instead use a 0.33 share for labour and for capital (when capital prices are available) and equal shares for the remaining factors of production. The same was true for the other variations we tried, such as 0.5 labour share, 0.25 capital share when capital prices were available, and equal shares for the other factors. The reason is clear: the resulting indexes of prices relative to the factors of production are always highly correlated.

[23] As Clark, 'Great escape', p. 47 (see above, n. 2), points out, industries such as printing did witness striking technical change in the early modern period, but they were relatively small. The military, however, was a major part of the economy, at least in Europe.

[24] Ibid., p. 69, tab. 1; Hoffman, *Growth*, pp. 130–1, tabs. 4.8 and 4.9; Mokyr, *Gifts of Athena*; Allen, *Enclosure*.

[25] Crafts and Harley, 'Output growth', p. 718, tab. 5.

[26] See Hoffman, 'Europeans' (see above, n. 20), for details.

Table 2. *Estimated rates of total factor productivity growth from regression of* ln(p/q)

Military good with price p	*Non-military good with price q*	*Period*	*Total factor productivity growth (% per year/t-statistic)*	*Factors of production in addition to skilled labour*	*N*
France					
Artillery	Lathing nails	1463–1785	0.7/4.95	Copper, capital	25
Muskets	Lathing nails	1475–1792	0.4/1.34	Iron, capital	37
Gunpowder	Lathing nails	1359–1765	0.3/1.95	Capital	68
England					
Artillery	Spades	1382–1439	2.4/8.65	None	10
Muskets	Spades	1620–78	1.6/3.49	None	7
Pistols	Spades	1556–1706	1.1/4.85	Iron, capital	12
Gunpowder	Spades	1515–1791	0.8/9.29	Capital	62

Notes: The regressions are based on equation (3); see the text for details. N is the number of price observations for the military goods; where there were more than 10 observations, the regressions were run with additional factors of production other than skilled labour. The other factors of production were ones whose prices could be found and for which factor shares were likely to be different for the military good and the comparison good.
Sources: English spade and gunpowder prices were kindly furnished by Greg Clark; the interest rates used in calculating the rental cost of capital for gunpowder came from his 'Agricultural', (see tab. 1). The French lathing nail and gunpowder prices are from d'Avenel, *Histoire économique*, and the legal maxima interest rates used in calculating the cost of French capital came from Guyot, *Répertoire universel*, vol. 15, s.v. 'Rente'. All the other prices come from the sources used for table 1.
It was difficult to find prices for the military and non-military goods on the same date, and for that reason, I calculated the price of the non-military goods by computing averages over long periods. In particular, for France, the lathing nail prices (from d'Avenel, *Histoire économique*) were averages over 50-year periods; iron prices and masons' wages (both from Levasseur, *Les prix*) were averages over 25-year periods. There were no lathing nail prices available for 1650–99. For England, prices of iron and spades were 25-year averages. The price of gunpowder was clearly influenced by warfare and the price of saltpetre; the table does not take that into account.

d we get from equation (3) will underestimate productivity growth for the military good. The key, of course, will be finding non-military goods with factor shares similar to those of the military goods—ideally, non-military goods whose production functions did not change.

This we can actually do (table 2). The regressions now involve not just the prices of French and English handguns and artillery, but gunpowder too. The prices of the English military goods are expressed relative to the cost of spades, a non-military good that presumably had factor shares roughly similar to those involved in the production of handguns, for, like spades, handguns were made of wood and metal. Admittedly, the factor shares were probably different for artillery and gunpowder, and it no doubt took more metal to make a firearm than a spade, but even cannons had wooden carriages, and wooden and metal tools were used to manufacture gunpowder. Despite these disadvantages, though, using the price of spades has certain virtues. Technical change in their production was probably small before the eighteenth century, and there are repeated price observations for spades with relatively little price variation at any given time.[27] Where we have enough data, we can compensate for the different factor shares for iron in military goods by adding the relative price of iron to the regressions.

For French military goods, prices are compared to the cost of lathing nails. Although the price of something like spades might have been a better non-military yardstick for handguns, it proved impossible to find prices for spades or any other

[27] Greg Clark, who provided the prices for spades, has posted his price data on the Global Price and Income History Group web site, at http://gpih.ucdavis.edu/Datafilelist.htm, in the file 'England prices and wages since 13th (Clark)'. His data set includes 352 observations of spade prices between 1221 and 1865, and each 25-year period from 1225–49 on has at least three price observations.

good made out of both wood and metal. Lathing nails, however, are not a bad choice for artillery, or for handguns either. Like the fabrication of handguns, the making of nails required metal and skilled labour and it also consumed wood for heating the furnaces. Lathing nails also had to serve as the non-military good for French gunpowder, which is obviously less satisfactory, but at least here it was possible to compensate for what were probably different capital intensities by adding the rental price of capital. In addition, because the technology of nail making may have begun to change as early as the seventeenth century, all of the comparisons between the price of nails and the price of French artillery, handguns, and gunpowder may well underestimate productivity growth for the military goods.[28]

Like the prices of arms and gunpowder, the prices of the various non-military goods used as yardsticks were fragmentary and not available for the same years for which prices of arms and gunpowder could be found. To solve this problem, 50-year averages of the lathing nails prices were taken to serve as the non-military yardstick in France, and 25-year averages of French skilled wages and iron prices. In the case of England, 25-year averages for the price of iron and spades were used.

Once again the estimated rates of total factor productivity growth are large by early modern standards (table 2). The lowest is 0.3 per cent per year, and the highest 2.4 per cent per year, which rivals the rates achieved in textiles and iron during the industrial revolution and would be respectable even by modern standards. The evidence, once again, points to rapid and sustained productivity growth over periods ranging from the fourteenth to the eighteenth century.[29]

It is true that the number of observations in table 2 is small, and the productivity growth estimates could be biased (either up or down) by variables that are omitted from the underlying regressions.[30] Suppose, however, that the seven estimates in table 2 were purely random. The smallest one is 0.3 per cent per year, and the other six exceed 0.4 per cent per year. The probability of that happening by chance are only 0.06, even if the estimates are drawn randomly from a population whose median is 0.4 per cent per year. In other words, productivity was unlikely to have been growing at less than 0.4 per cent per year, a swift pace for a pre-industrial economy.

[28] See the eighteenth-century *Encyclopédie* of Diderot and d'Alembert, eds., vol. 3, pp. 548–51, s.v. 'Clou'; Chisholm, ed., *Encyclopaedia Britannica*, vol. 19, pp. 153–4, s. vs. 'nails'; and Mokyr, *Lever of riches*, p. 62. Although the *Encyclopédie* article does not show any obvious signs of a change in the way nails were made in mid-eighteenth-century France, the division of labour may have already progressed.

[29] Other ways of looking at the price data lead to similar results. The outcome is much the same, for instance, if we try to put a lower bound on total factor productivity growth by maximizing the amount of the decline in the price of military goods that can be accounted for by cheaper factors of production. For details, see Hoffman, 'Europeans' (see above, n. 20).

[30] Gunpowder is one case where factor prices might cause enough bias to account for the negative time coefficient. The reason is that the price of saltpetre, a major component of gunpowder, declined during the early modern period, at least in England. The problem then, however, is explaining why the saltpetre prices dropped. Saltpetre was one of the rare commodities for which intercontinental transport costs dropped before 1800 (O'Rourke and Williamson, 'When did globalization begin?'), and if productivity was not growing in gunpowder production, then it was in the production of saltpetre and its transport from places like India. Rathgen, *Das Geschütz*, pp. 93–9, provides evidence that in the late fourteenth and early fifteenth centuries German cities devised ways to produce saltpetre domestically at low cost rather than buying expensive imported saltpetre.

Table 3. *Military labour productivity in the French army: rate of successful fire per infantryman, 1600–1750*

Approximate date	*Rate of successful fire per handgun (shots/minute)*	*Handguns per infantryman*	*Rate of successful fire per infantryman (shots/minute)*	*Assumptions*
1600 (1620 for handguns per infantryman)	0.50	0.40	0.20	1 shot per minute with matchlock; 0.50 misfire rate
1700	0.67	1.00	0.67	1 shot per minute with flintlock, 0.33 misfire rate; bayonets have led to replacement of pikemen
1750	2.00	1.00	2.00	3 shots per minute with flintlock, ramrod, and paper-cartridge; 0.33 misfire rate

Notes: The calculation considers only pikemen and infantrymen with firearms; it ignores unarmed solders, such as drummers. The implied rate of labour productivity growth over the 150-year period from 1600 to 1750 is 1.5% per year.
Source: Lynn, *Giant of the Grand Siècle*, pp. 454–72.

Furthermore, there is good reason to believe that the figures are in fact biased downward. As we have mentioned, the prices we have selected gloss over naval warfare, where western Europe's progress and comparative advantage were probably greatest. They also exclude any correction for progressive improvements in the quality of weapons, which would lead us to understate any productivity gains, particularly for handguns.[31] The French firearms prices illustrate how such an underestimate could arise. In the late seventeenth and eighteenth centuries, the French prices are for flintlock handguns, which replaced older matchlock muskets and arquebuses.[32] However, firing a flintlock was much easier, for the soldier no longer had to go through some 32 steps while holding a lighted cord in his fingers and keeping it from causing his weapon to misfire. The advantage of the flintlock should have pushed its relative price up, and with more data, it might have been possible to correct for the improvement by adjusting the price of the flintlock downward to make it comparable to the older muskets. Because this was not done, the firearm data underestimate the rate of productivity growth.

The magnitude of the resulting underestimate is sizeable. Thanks to the flintlock and other improvements, firing rates increased and misfires diminished, and as a result, armies' labour productivity soared. In the French army, the rate of successful fire per soldier jumped 10-fold between the early seventeenth century and the middle of the eighteenth century (table 3), for an overall labour productivity

[31] As the price data for handguns were being gathered, careful attention was paid to the vocabulary to guard against unsuspected changes in the weapons' characteristics. Fortunately, as Europeans experimented with different types of handguns, they coined a wide variety of words to distinguish different calibres and firing mechanisms. The lists of handguns in d'Avenel, *Histoire économique*, vol. 6, pp. 574–9, use this broad vocabulary, and also seem to distinguish atypical firearms that were specially crafted for wealthy purchasers. One does have to watch, though, for changes in meaning: a mousquet (musket) started out as a large calibre weapon in the early seventeenth century, but by the middle of the century it had become nearly synonymous with the smaller calibre arquebuse (arquebus).

[32] Hall, *Weapons and warfare*; Lynn, *Giant of the Grand Siècle*, pp. 454–72.

growth rate of 1.5 per cent per year. The flintlock itself accounted for only some 13 per cent of this 10-fold increase; the rest came from inventions such as the ramrod, the paper-cartridge, and the bayonet, which made it possible for armies to do away with pikemen and to arm more and more of their soldiers. However, none of this 13 per cent gain figures in the total factor productivity growth rates in table 1 or table 2.[33]

One last reason why our rates of productivity growth may be biased downward deserves to be stressed, even though it too has already been mentioned. It is the simple fact that price data for a new weapon (as we noted above) will typically not appear in historical records until well after it is first invented, and that means after the period when costs of production are likely to be falling most rapidly thanks to learning by doing.[34] Fortunately, we have one instance where we can verify that this took place, for some of the first handguns that were ever made—in this case, arms produced in Frankfurt during the years 1399–1431. Thanks to the meticulous research of Rathgen, an artillery officer and military historian who died in 1927, we actually have prices for the handguns, along with the wages paid to the metal workers who cast them and the cost of the copper which served as the raw material. These early guns resembled small cannons with barrels less than 500 millimetres long. Although they were not very effective, cities like Frankfurt bought them in large numbers since they could be fired against attackers from the top of thin medieval walls.[35]

For these early handguns in Frankfurt, we actually have enough data to estimate equation (1) with prices for all the factors of production included among the explanatory variables.[36] When we run the regression (table 4), we end up with reasonable coefficients (the factor share for copper is 0.307) and a rate of total factor productivity growth of 3.0 per cent a year, which is more rapid than what was achieved by the most dynamic sector of the British economy—the cotton textile industry—during the industrial revolution.[37] We know why productivity was climbing so fast: the metal workers were learning how to make the handguns with less copper, which cut the price of the guns drastically. To us, such an improvement may seem obvious, but given the frequency with which early cannons exploded and maimed gunners, it was a step that the gunsmiths must have taken with a great deal of trepidation.

[33] See tab. 3; Lynn, *Giant of the Grand Siècle*, pp. 454–72; Chase, *Firearms*, p. 25, 74, 226. Other physical measures of productivity, such as the ease with which cannons could be transported, also soared. Firing rates and cannon mobility bring us much closer to what we would ideally be measuring—military effectiveness—and they in fact suggest that if effectiveness is the yardstick, then the military's labour and capital productivity were both increasing.

[34] Lucas, 'Making a miracle'.

[35] Hall, *Weapons and warfare*, p. 95; Rathgen, *Das Geschütz*, pp. 68–74.

[36] The meagre evidence that exists suggests that long-run interest rates may perhaps have been declining during the years 1399–1431, but very slowly: Winter, 'Abhandlungen'. I have therefore assumed that the interest rate was constant, as was the rate of depreciation, and that the sales price of capital was proportional to the skilled wage. Under these assumptions, the rental price of capital divided by the wage will be a constant, and its coefficient in equation (1) will be part of the constant term a. From Rathgen's description, the city of Frankfurt did not seem to act like a monopsonist; in particular, it sometimes bought guns from other nearby cities, where the prices were similar. In any case, even monopsony would not cause a problem, so long as entry were free, and Rathgen's evidence suggests that the gunsmiths and metal workers changed over time and came from other cities as well: Rathgen, *Das Geschütz*.

[37] Harley, 'Reassessing', pp. 717–19; Broadberry, 'Total Factor Productivity', pp. 130–1.

Table 4. *Regression of the relative price of early handguns in Frankfurt on time and the price of copper, 1399–1431*

Coefficient in equation (1) and associated explanatory variable	*Coefficient/t-statistic*
a (the constant term)	45.062/6.39
b (the year; the opposite of the coefficient is then the total factor productivity growth rate)	–0.030/5.92
s_1 (the logarithm of the price of copper relative to the skilled wage; the coefficient is then the factor share for copper)	0.307/1.98
R^2	0.73
Adjusted R^2	0.69
Standard error	0.19
Observations	21

Notes: The dependent variable is the logarithm of the price of the handguns divided by the skilled wage. As noted in the text, it has been assumed that the interest and depreciation rates were constant and that the sales prices of capital were proportional to the skilled wage. The rental price of capital relative to the skilled wage is then constant, and its coefficient becomes part of the constant term.
Sources: The data come from Rathgen, *Das Geschütz*, pp. 68–74. The wages used were actually a piece rate (the money paid to the metal worker to cast a pound of copper). If metal workers got better at casting in general, then the regression would underestimate the rate of productivity increase. For some of Frankfurt's purchases, the accounting was incomplete, and Rathgen had to assume that the wage rate or price of copper was the same as in other transactions at nearby dates. I have used the prices he calculated for the handguns except in a few instances where his extensive quotes from the archives suggest that the prices were different; these differences were always small.

II

The relative price of military goods was thus falling in late medieval and early modern Europe, a mark of rising productivity in the military sector. However, in order to be convinced that this productivity growth can help explain Europe's comparative advantage in violence, it would be reassuring to have information about prices for military goods elsewhere in the world, particularly in the other advanced Eurasian economies. Did the weapons industries in east Asia, south Asia, or the Ottoman Empire fall behind as Europe specialized in making better cannons and handguns at a lower cost?

Ideally, we would like to find similar series of weapons prices and factor costs for other major Eurasian economies. Although a few fragmentary figures exist outside of Europe, it has nonetheless been impossible to construct the sort of data on factor costs and the prices of military goods that would allow the calculation of productivity growth rates for east Asia, south Asia, or the Ottoman Empire. Even comparing relative prices is next to impossible, although there are a few for Chinese and Indian muskets that permit a tentative comparison. The Chinese prices, which come from ongoing research by Bozhong Li, derive from estimates made by Xu Guangqi, a Chinese official and Christian convert, who in the waning years of the Ming Dynasty proposed that the Chinese army should adopt western arms and tactics to defend itself against the growing power of the Manchus.[38] If we

[38] For Xu and the Chinese context, see Needham, *Science and civilisation*, vol. 5, pt. 7, pp. 392–407; Twitchett and Fairbank, eds., *Cambridge history of China*, vol. 8, p. 352. Bozhong Li (personal communication) found the Chinese musket prices in Xu Guangqi's 'Memorials to the Ming Emperors', in *A collection of Xu Guangqi* (Shanghai, 1984), pp. 124, 294.

Table 5. *Relative price of handguns in Europe and Asia*

Year	*Place*	*Weapon*	*Price (grams silver)*	*Food*	*Price (grams silver/1,000 calories)*	*Calories/gun (England 1620–21 = 100)*	*Calories/gun (England 1620–21 = 100): Correction for using flour*
1619	China	Matchlock muskets	150	Rice	0.108	549	345
1630	China	'Hawk muskets'	374	Rice	0.174	852	535
1601–25	France	Matchlock muskets	86	Wheat flour	0.353	96	96
1626–50	France	Matchlock muskets	117	Wheat flour	0.471	98	98
1620–1	England	Muskets	76	Wheat flour	0.302	100	100
1819	India	Guns	54	Wheat flour	0.426	50	50
1796–1807	Britain	Guns exported to Africa	74	Wheat flour	0.861	34	34

Sources: The weapons prices from China were provided by Bozhong Li, who gathered them from Xu Guangqi's 'Memorials to the Ming Emperors' in *A collection of Xu Guangqi* (Shanghai, 1984), pp. 124, 294. Those from India were furnished by Peter Lindert, from data (originally collected by David Jacks) that came from V. D. Divekar, *Prices and wages in Pune region in a period of transition, 1805–1830 AD* (Pune, Gokhale Institute of Politics and Economics, 1989). The European weapons prices come from Inikori, 'Import of firearms', p. 346, tab. 2, for Britain in 1796–1807, and the sources in tab. 1 for the other years. The food prices and calorie equivalents came from the following sources at http://gpih.ucdavis.edu/Datafilelist.htm: for China, Guanglin William Liu's Peng series of decennial average rice prices, in the file 'China, rice prices 961–1910 (Liu)'; for France, 25-year averages of the Paris wheat prices that Philip T. Hoffman calls wheat 2, in the file 'Paris 1380–1870'; for England, the wheat and flour prices collected by Greg Clark, in the file 'England prices and wages since 13th (Clark)'; and finally, for the conversion of volumes to weights, the equivalents in the file 'Weight vs. volume'. The English wheat and flour prices were used to convert wheat prices to flour prices when flour prices were unavailable in India and France. Calorie equivalents (3,620 calories per kilogram of rice, 3,390 calories per kilogram of wheat flour) came from Allen, Bassino, Ma, Moll-Murata, and van Zanden, 'Wages, prices, and living standards', tab. 7.

If multiple prices were available, I chose those that biased the results against finding a higher relative price for weapons in China and India. The wheat price used for Paris, for instance, was generally lower than the alternative price that Hoffman gives for Paris wheat during the same period, the price he labels wheat 1. When flour prices were unavailable, wheat prices were converted to flour equivalents using the average price ratio of a kilogram of flour to a kilogram of wheat (1.591) during the years 1600–30 in Clark's data set. The British prices in 1796–1807 are the averages for low-quality weapons exported to Africa.

compare his estimates to contemporary prices for muskets in France and England, handguns turn out to have been three to nine times more expensive in China, at least when measured relative to food. Data from early nineteenth-century India also suggest that the relative price of handguns was higher in Asia, although the price difference had diminished (table 5).

These prices are perhaps too scanty to serve as the basis for any conclusions, or at least any firm ones.[39] Also, one might worry that food is not the appropriate yardstick for price comparisons.[40] However, there is abundant indirect evidence that leads to a similar conclusion, even if we ignore table 5. The indirect evidence comes from what we know about the early modern trade in military goods and services, which—at least as far as the gunpowder technology is concerned—flowed from Europe to the rest of the world and not in the reverse direction. Artillery and

[39] In particular, the 1630 Chinese price might be for a special weapon and therefore be high, which would bias the result in favour of finding lower relative prices of weapons in Europe. For comparison of India and Britain, the relative price of the British weapons may have been driven down by the high cost of food during the Napoleonic wars and the low quality of the British guns, which were destined for export to Africa. On the other hand, war would have driven up the price of the British weapons, and if the British prices had been measured in 1819 (like the Indian price), and not in 1796–1807, they might have been even lower because of productivity growth in the wartime armaments industry.

[40] Food was relatively expensive in Europe, particularly processed food such as flour. Tab. 5, though, also adjusts the Chinese figures to show what the relative price differences would have been had prices of wheat been used rather than flour. The adjustment reduces the striking difference in relative prices somewhat, but does not eliminate it. For India, the relative price in 1819 is measured relative to flour, as in Britain in 1796–1807.

handguns were certainly produced in early modern Asia and the middle east, as were fortifications and armed ships. There was also trade within Asia in these military goods and in the services of the experts who made them. However, if one looks at western Europe's role in this traffic, it was an exporter, not an importer, particularly when it came to the cutting edge technologies.[41] It must have therefore had a comparative advantage in the gunpowder technology. That sort of comparative advantage is precisely what we would expect if long-run productivity growth in the military sector (at least when it came to using the gunpowder technology) had been more rapid in Europe than in Asia.

The evidence about this trade is qualitative and based on contemporary comments and studies by modern historians, but it does seem strong. Consider, for example, the Ottoman Empire: although it had 'robust ordnance industry', it nonetheless imported weapons from western Europe and often relied on the expertise of European military specialists. Even a historian who argues that the European technological superiority over the Ottomans was minimal, at least until the late seventeenth century, admits that it was 'European military experts who sold their expertise to the Ottomans and not vice versa'.[42]

Alternatively, consider Jesuits in seventeenth-century China who were asked to help produce better artillery. Their knowledge of cannon founding came, they said, from books alone, but it was still useful to both Ming and Qing emperors. The advantage they had, it should be stressed, was not any superior skill in casting metal, for the weapons were actually produced by skilled Chinese craftsmen, who were arguably just as proficient as (if not superior to) the best foundry workers in Europe. Rather, it was that the Jesuits' books provided information about the design and testing of cannons.[43]

That knowledge, which had been acquired by experience and learning by doing in European wars, was in all likelihood a major source of the European's comparative advantage in the manufacture and use of gunpowder weapons. Europe's comparative advantage in manufacturing capital-intensive weapons may have also stemmed from a lower relative price of capital, although there is no way to tell for sure without better evidence about factor costs. In any case, the knowledge gained from experience would have boosted productivity in the European military sector and led Europe to specialize in gunpowder technology, and it would have been augmented by investments made by European states that were eager to learn even more. Europe would have then exported this technology, just as developed economies do today when they specialize in different products and end up trading with other countries whose factor prices may be the same as theirs.[44] The pattern of

[41] The one exception is saltpetre, which was imported into Europe from south Asia.

[42] Agoston, *Guns for the sultan*, pp. 10–12, 193–4.

[43] Josson and Willaert, eds., *Correspondance*, pp. 37–43, 99–118; Parker, *Military revolution*, pp. 131–2, 226; Spence, *To change China*, pp. 15, 29; Väth, *Johann Adam Schall Von Bell*, pp. 361–77; Needham, *Science and civilisation*, vol. 5, pt. 7, pp. 392–8. According to Bozhong Li (personal communication), when Xu Guangqi proposed that the Chinese army adopt western arms, his plan was not to purchase cannons from Europeans. Rather, he simply wanted to purchase plans for western artillery from the Europeans and to have them test the weapons, which would be manufactured in China.

[44] For an overview of the relevant trade literature here, see Helpman, 'Structure of foreign trade'. Such specialization derives from economies of scale, which can arise from learning by doing or from investment in research and development.

trade that we observe may of course have arisen from other causes—including different factor prices—but it is at least consistent with more rapid productivity growth in the European military sector.

The trade, it should be stressed, involved far more than just weapons. The Europeans also exported expertise and human capital, as gunfounders, officers, soldiers, sailors, and military architects travelled to Asia to sell their skills. In India, it is claimed, there were in 1565 some 2,000 renegades and mercenaries from Portugal alone, who, along with other Europeans, sold weapons and passed along military tactics.[45] Admittedly the Europeans in India only had a limited effect initially, in large part because warfare there often involved highly mobile cavalries, against which the gunpowder technology was of little use. However, their impact was enormous in the late eighteenth century, when European officers and lighter European field artillery helped make the gunpowder technology more effective on south Asian battlefields.[46] Again, it was the experience gained using the gunpowder technology in European wars that gave Europe's military sector its comparative advantage.

Asserting that Europe's military sector experienced more rapid productivity growth does not mean that productivity advances were unknown in armies or navies elsewhere in the world. The evidence—falling military prices in Europe, and the pattern of military trade between Europe and Asia—concerns only gunpowder technology, not other methods of fighting, which could well improve.[47] There were certainly other economies that advanced gunpowder technology too: China, which invented it, is an obvious example, as is Japan, which discovered volley fire before the Europeans.[48] However, the pattern of trade suggests that productivity growth was sustained much longer in Europe, which helped give the Europeans their comparative advantage in violence.

III

If the evidence is persuasive, we still have to explain why it was Europe's military sector that experienced rapid and sustained productivity growth, at least in using gunpowder technology. We must also ask whether productivity growth is enough to account for Europe's conquest of the world.

A satisfactory response to these two questions would require more than a single article, but we can at least sketch some answers.[49] To begin with, productivity growth in the manufacture of gunpowder weapons cannot by itself account for Europe's conquests. Much more was involved, including all the advances in tactics, training, logistics, and war finance that made the European military more

[45] Subrahmanyam, 'Kagemusha effect'.

[46] Bidwell, *Swords for hire*; Cooper, *Anglo-Maratha campaigns*; Fazl 'Allami, *Ain i Akbari*; Gommans, *Mughal warfare*; Gommans and Kolff, eds., *Warfare and weaponry*.

[47] For an example, see Gommans, *Mughal warfare*, pp. 129–64, which recounts how the Mughals came to stress accuracy of fire with long matchlocks they had developed. Their matchlocks and tactics proved effective in Indian warfare until the late eighteenth century.

[48] Chase, *Firearms*; Parker, *Military revolution*, pp. 115–45.

[49] For more on why Europe's military sector experienced more rapid productivity growth, see P. T. Hoffman, 'The politics and economics of Europe's comparative advantage in violence', global price and income history working paper 13 (2003), URL http://www.gpih.ucdavis.edu/files/Hoffman2.pdf [accessed 5 Sept. 2009].

effective yet had nothing to do with the production of military goods.[50] Fortifications are a clear example. Although construction techniques may not have improved, designs certainly had, and so too had the fiscal apparatus that paid the bills. Much the same could be said of ship design or supply chains in navies, which had also benefited from better organization. In the British navy, a system of rewards for captains and crew reduced the commanders' mortality rate and helped make the eighteenth-century British ships the most effective in the world. The captains' growing experience in naval combat also gave them an edge.[51] A broader definition of productivity could encompass many of these other improvements, but not all of them, and it would also leave out the historical accidents that worked to Europe's advantage, such as the divisions among the powers confronting Europeans elsewhere in the world.[52]

Still, rapid productivity growth in the military sector was a major part of the story behind Europe's conquests, particularly if the definition of productivity is expanded beyond the manufacture of weapons to encompass all the organizational improvements that accompanied gunpowder technology. The question then would be why productivity broadly defined grew so rapidly in the European military sector.

One frequently invoked explanation is the competition among European states, which fought practically incessantly between the late middle ages and the end of the Napoleonic wars. The argument, which dates back to Gibbon, has been formulated most cogently by Kennedy, who points to Europe's competitive markets and persistent military rivalries. While military rivalry created an arms race, competitive markets encouraged military innovation and kept any one country from establishing an empire.[53]

Although that is a step in the right direction, we still need to know why the competition translated into productivity growth in the military sector. After all, there were sectors of the early modern economy with highly competitive markets—agriculture in France is one example—and yet virtually no productivity growth. What kept farmers from reaping the productivity gains of soldiers and sailors? Furthermore, other parts of the world seem to have experienced military rivalries—south-east Asia in the eighteenth century, Latin America in the nineteenth—without having innovative military sectors.[54] What was peculiar about the European competition? Why did it generate productivity growth and a comparative advantage in using the technology of artillery, firearms, fortifications, and navies?

What made the European military rivalry unusual was that it was a tournament—the sort of contest in which the winner takes a prize and the other competitors receive nothing.[55] If the prize is large, a tournament can induce the

[50] Black, *War and the world*.
[51] Benjamin and Tifrea, 'Learning by dying'.
[52] Black, *War and the world*.
[53] Ibid., pp. 3–7; Kennedy, *Rise and fall*, pp. 16–24.
[54] For French agriculture, see Hoffman, *Growth*, and for south-east Asia, see Andaya, 'Interactions with the outside world'.
[55] What follows is a brief summary of the argument and evidence in Hoffman, 'Politics and economics' (see above, n. 49).

competitors to exert enormous effort in the hopes of winning, and for that reason tournaments are used today to encourage innovation, as when choosing the manufacturer of a new jet fighter.

In early modern Europe, the tournament's potential contestants were the kings and princes who decided whether or not to go to war; the prize for victory was military glory and revenue from conquered territory. The sovereigns had every reason to enter the contest. They (and much of the aristocracy) had been raised since childhood to pursue glory in war, and they bore little risk in case they lost, at least in the major states. Therefore they made an enormous effort not just to ameliorate their gunpowder weapons but also to bring about all the other improvements that were part of the military revolution. In particular, they raised taxes and tried to centralize the fiscal system and military logistics, for the gunpowder technology was most effective if spending was focused on key ports, a limited number of border fortresses, and large consolidated armies. They invested heavily in improving tactics, weapons, and logistics. When the tournament was over, they would copy the tactics, weapons, and organization of the victor, and the tournament would begin another round, which yielded further advances.

Elsewhere conditions did not foster such a tournament. There might be military rivalry—as in eighteenth-century India—but the political costs of raising taxes and centralizing the fiscal system were too high. Or if there were a tournament, one contestant might end up conquering all the others and thus putting an end to the contest. That happened with the Tokugawa Shogunate in Japan and in China when dynasties were strong. Another possibility is that the relevant military technology might not be amenable to improvement. That too was the case in China, where the major enemies were nomads from the north. Against them, gunpowder technology was of little use. Mounted archers or cavalry with swords were far more effective, but the relevant weapons and tactics changed little until the invention of the repeating rifle in the nineteenth century.[56] So even when there was a tournament, it did not produce the productivity gains achieved in Europe.

IV

To assert that military production experienced surprising productivity growth in late medieval and early modern Europe of course fits what at least some military historians claim when they write about the military revolution.[57] However, the price trends and productivity estimates have important implications for economic history too. There the sustained pre-industrial productivity growth is the great surprise, particularly since it concerned a major sector of the economy and reached back perhaps four centuries before the onset of the industrial revolution. The rates of total factor productivity growth were substantially higher than the 0.1 per cent or less that characterized most pre-industrial economies. Why did all the productivity growth in the military realm not spark economic growth elsewhere in the economy?

It was not, to repeat, that the military sector was small. In 1752, for example, French military expenditure amounted to somewhere between 3 and 7 per cent of

[56] Chase, *Firearms*.
[57] Black, *Military revolution*.

GDP (a fraction comparable to defence spending in the US or the USSR at the end of the Cold War) despite it being a year of peace. Figures in other European countries were similar and of course soared even higher in wartime,[58] but the incessant warfare that resulted from all this spending ended up interfering with trade and destroying enormous amounts of capital in other parts of the economy.[59] The growth in the military sector was more than cancelled out by the damage done by war.

Here one could even ask whether a dynamic military sector possibly delayed economic growth by diverting talent and resources to destructive activity. Mokyr has argued that warfare did not spur technical change in the civilian economy, but perhaps the toll war took was even greater than he supposed.[60] A careful assessment would of course have to take into account conceivable positive spillovers from the military sector in areas such as machining and metallurgy or in the security that navies provided for international trade. Those spillovers were perhaps larger in eighteenth-century Britain than on the continent, since Britain escaped most of the harm that land war caused. The assessment would also have to acknowledge that borrowing for warfare helped create European financial markets. But it would entail calculating whether the poor economies of early modern Europe were massively overinvested in the military. What would have happened to western European economies if the resources and talent that worked such wonders in the military sector had instead been allocated to the civilian economy? Could they (and perhaps even some of the military technology) have found ready application in civilian enterprises? If so, could this help explain why western Europe industrialized rapidly after 1815, when a century of relative peace allowed talent and inventive effort to shift to civilian use?

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[58] The 1752 figures come from Riley, *Seven Years War*, pp. 57–8, using Riley's 1747 and 1757 GDP estimates. The 7% figure uses the lower 1747 GDP estimate and includes spending on foreign affairs and payments on past war debt in the military total. The 3% figure excludes debt payments and foreign affairs and relies on the higher 1757 GDP estimate. For military spending elsewhere in early modern Europe, see Hoffman and Rosenthal, 'Political economy', p. 36. For military spending *c.*1991 in the US (4.9% of GDP) and the USSR (10.3%), see Hartley and Sandler, eds., *Handbook*, vol. 1, p. 59.

[59] For examples of how warfare destroyed capital and interfered with trade, see Hoffman, *Growth*, pp. 185–6, 202–3.

[60] Mokyr, *Lever of riches*, pp. 183–6, 207–8.

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