Technological Change and Obsolete Skills: Evidence from Men's Professional Tennis*

Ian Fillmore†   Jonathan D. Hall‡

September 20, 2021

Abstract

Technological innovation can raise the returns to some skills while making others less valuable or even obsolete. We study the effects of such skill-altering technological change in the context of men's professional tennis, which was unexpectedly transformed by the invention of composite racquets during the late 1970s. We explore the consequences of this innovation on player productivity, entry, and exit. We find that young players benefited at the expense of older players and that the disruptive effects of the new racquets persisted over two to four generations.

JEL: J24, O33, Z22

Keywords: Technological Change, Human Capital, Tennis

---

†Washington University in St. Louis, ianfillmore@wustl.edu.

‡University of Toronto, jonathan.hall@utoronto.ca.

1 Introduction

The last two centuries have witnessed an enormous amount of technological innovation, and this is widely viewed as the primary source of long-run economic growth and improvements in well-being. At the same time, at least since Ricardo, economists have recognized that innovation can also be disruptive. As Acemoglu (2002) vividly states, "in nineteenth-century Britain, skilled artisans destroyed weaving, spinning, and threshing machines during the Luddite and Captain Swing riots, in the belief that the new machines would make their skills redundant. They were right: the artisan shop was replaced by the factory and later by interchangeable parts and the assembly line." New technologies disrupt the labor market when they raise the returns to some skills while making others less valuable or obsolete.

We develop a theory, inspired by MacDonald and Weisbach (2004), of this phenomenon, which we call skill-altering technical change. Our theory emphasizes that workers endogenously invest in a portfolio of skills over their life cycle. We show that new technologies that change the relative values of skills can hurt older workers, who have spent a lifetime investing in the old, ideal skill mix, and better workers, who, by definition, possess more of the skills that were previously more valuable. We find that, depending on the elasticity of demand for workers' output, the effect of a new technology can either increase or decrease exit rates and cross-sectional inequality. Moreover, the specter of future, skill-altering change makes current human capital investment risky, especially investment in specialized skills.

To test our model's predictions empirically and quantify the effects of skill-altering technical change, we exploit the introduction of composite racquets in men's professional tennis during the late 1970s and early 1980s. These new racquets drastically changed the way the game was played, increasing the importance of hitting with spin and power relative to control. There are four reasons this episode in men's professional tennis is a useful setting to study the effects of skill-altering technological change on workers. First, we have detailed panel data on multiple cohorts of individual workers (players), allowing us to track the impacts of skill-altering change over multiple generations of workers. Such data is difficult to obtain in most settings. Second, the new technology arrived suddenly and unexpectedly and

was adopted universally within a few years. This is valuable because the timing of the innovation is obvious, the speed of the transition reduces the concern that other economic shocks are driving the results, and this particular innovation was specific to tennis, thereby minimizing concerns about general equilibrium effects. Third, tennis careers are short—six years on average and rarely more than fifteen years—which allows us to follow multiple cohorts of players over their entire careers. Another advantage of short careers is that it further reduces the concern that other economic shocks are driving the results. Fourth, since we can observe the performance of a player without worrying about the effects of teammates, professional tennis offers unusually clean measures of worker productivity.

We find that the introduction of the new composite racquets substantially disrupted the tour, with repercussions lasting for between two and four generations. It temporarily reduced the rank correlation in player quality over time, helped younger players at the expense of older ones, reduced the average age of tennis players, and increased exit rates of older players relative to younger ones. We find that intergenerational inequality rose, though we find mixed evidence for the new racquets' effects on cross-sectional inequality. We also consider competing explanations, but we conclude that they cannot explain many of the other patterns we find. Moreover, when we compare the ages of tennis players with other Olympic athletes, we do not find a similar drop in the ages of Olympic athletes during the same time period.

While tennis provides an ideal setting for documenting skill-altering technical change, the phenomenon extends far beyond tennis. Consider the case of farmers during the mid-twentieth century. It is difficult to overstate the effect of the rise of tractors on the nature of farming. While tractors made all farmers more productive, they also had subtler effects on optimal farming practices. With a tractor, the traditional approach to farming, which relied on work animals, gave way to new farming techniques that relied on machines. Thus, farmers who had spent a lifetime investing in animal husbandry skills saw the value of their skills eroded by the arrival of tractors. As another example, consider the development of computer-aided drafting in architecture during the 1980s, discussed in MacDonald and Weisbach (2004). This new software devalued drafting and engineering skills relative to artistic skills when designing new buildings. Older architects found the transition difficult,

3

with the *New York Times* reporting that "as young architects plunge into the high-tech tide, older colleagues wade in gingerly."[1] In both examples, the new technology altered the relative value of different skills in an occupation. Consistent with skill-altering technical change, Figure 1 shows that the average age in those occupations fell temporarily relative to the general population just after the new technology arrived.

This paper contributes to the literature on skills and technological change, and to the more recent literature on the effects of labor demand shocks on workers. A large literature has explored the evidence and consequences of skill-biased technical change (SBTC), which Autor et al. (2008) define as "any introduction of a new technology ...that increases the demand for more-skilled labor relative to less-skilled labor at fixed relative wages." In contrast, the phenomenon we identify—skill-altering technical change—is the introduction of a technology that raises the demand for, or productivity of, one skill relative to another at fixed implicit (skill-specific) wages. Whereas models of SBTC make predictions about wage differences between, for example, college and non-college educated workers, our model of skill-altering change primarily makes predictions about wage differences between more- and less-experienced workers. Furthermore, because skill-altering technical change focuses on differential effects of technical change over the life cycle, it allows us to address intergenerational inequality and exit decisions. This allows us to address a puzzle Card and DiNardo (2002) identify; "SBTC also fails to explain ...the age gradient in the return to education" which we explain as resulting from a change in which skills are valued rather than a change in the general value of skill. Moreover, while the prospect of future SBTC raises returns to human capital investment, the prospect of future skill-altering change discourages human capital investment. Thus, while skill-biased and skill-altering change are not mutually exclusive phenomenon, they are conceptually distinct and offer distinct empirical predictions.

We build most closely on four papers that measure how the introduction of technology affects workers. Akerman et al. (2015) use the exogenous roll-out of broadband internet in Norway, Gaggl and Wright (2017) use variation induced by

---

[1]Dunlap, David. "Computer design: Castles, and planetariums, in the air." *New York Times.* 11 March 1999.
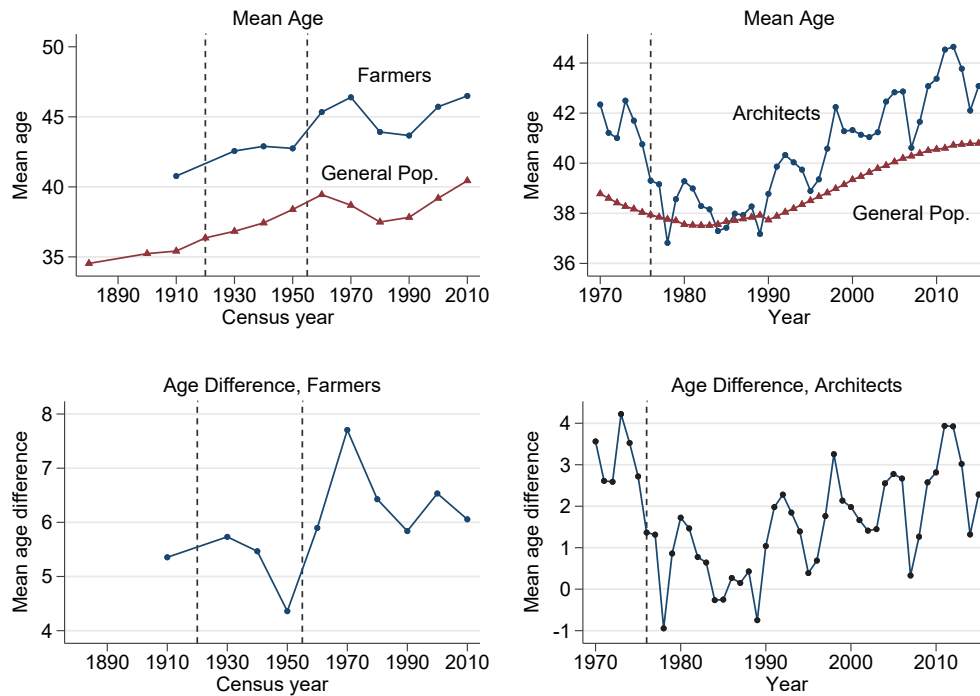
Figure 1: The rise of tractors and the arrival of architectural software

Source: United States Current Population Survey (Flood et al., 2017), United States Census, and American Community Survey (Ruggles et al., 2018)

Notes: Data on farmers come from the Census through 2000 and the five-year ACS (2008-2012) for 2010. Data on architects come from the March CPS prior to 1976, and from the basic monthly CPS thereafter. Samples restricted to ages 18–64. Tractors per farm rose from only 1 in 26 in 1920 to nearly 1 to 1 in 1955 (see Table 2 of Binswanger (1986)). We date the arrival of architectural software to 1976. The first computer-aided drafting programs were developed in the early 1960s, but were not used widely until much later. As late as 1977, firms could claim to be among the first in their state to be using computer-aided design (Zahler, Miriam. "Architects turn to computers for drafting and design work." *Crain's Detroit Business.* 13 October 1986).

an unexpected U.K. tax credit for small firms which invested in information and communication technology, Hanssen (2020) uses the transition to sound motion pictures, and Horton and Tambe (2020) use the transition away from Flash. We also build on Gannaway et al. (2014), who investigate the effects of a new technology in professional sports—the three-point line in NBA basketball. We build on these papers by introducing a model of skill-altering technological change and using panel data to trace its effects on workers over time, and examining how the effects differ based on worker experience.

The structure of the paper is as follows. We explain the nature of the technological shock in men's tennis in Section 2, and introduce our model in Section 3. In Section 4 we use this model to understand how players are affected by the introduction of a skill-altering technology. We introduce our data in Section 5 and describe how we estimate player quality using this data in Section 6. We test the predictions of the model in Section 7 and discuss our results and limitations in Section 8. Section 9 concludes.

2   Background

Until the mid-1970s, tennis racquets were made nearly exclusively of wood, and this technology had been stable for decades. Although alternative materials were tried, such as the steel Wilson T-2000, which a few players used, most players continued to play with wood racquets. Then a retired engineer, Howard Head, started playing tennis and discovered he was terrible at the game. He decided that the fault lay with his racquet, and in 1976, he took it upon himself to invent a new one, the Prince Classic. "With... my racket I was inventing not to just make money, but to help me."[2] Although initial reactions to Head's new racquet were laughter and scorn, the racquet had much to offer recreational players.[3] The Prince Classic had a larger string bed and sweet spot that made it easier for players to make good contact with the ball and generate more power and spin, but it achieved these gains at the expense

---

[2]Carlson, Bernie. "Howard Head And The Prince Tennis Racket: A Journey From The Personal To The Democratic." *Forbes.* 1 December 2017.

[3]Fisher, Marshall Jon. "The Feel of Wood." *The Atlantic.* July 1995.

of stiffness and control, making the racquet unacceptable for professional players. Racquet makers quickly found a solution; they developed methods for constructing the racquet frame out of a composite material consisting of a mixture of carbon fibers and resin. Composite frames allowed both a larger string bed and a stiff frame, giving players more power *and* control. The first composite racquet that professionals used, the Prince Pro, hit the market in 1978, and composite racquets quickly replaced wood ones as professional players found that their familiar wood racquets were no match for the combination of power and control afforded by the new composite racquets.

Figure 2 illustrates this transition by reporting the racquets used to win each of the four Grand Slam tournaments over time.[4] During 1981, Brian Teacher became the first player to win a Grand Slam using a composite racquet when he won the Australian Open using the ProKennex Black Ace. Just two years later at Roland-Garros, Yannick Noah became the last player to win a Grand Slam using a wood racquet. But at that point, even Noah's wood racquet had an oversized frame with graphite inlays added to increase stiffness. By 1983 the share of wood racquets accounted for only 25 percent of the high-priced racquet market,[5] and by 1984, composite racquets had taken over the tour.

The introduction of composite racquets significantly changed the way men's professional tennis was played. When tennis players strike the ball, they often try to impart topspin, which causes the ball to rise over the net and then dip downward, helping it stay in the court. Moreover, a ball hit with topspin "jumps" off the court, making it more difficult for an opponent to return. All else equal, the more topspin a player can impart, the harder he can hit the ball and still keep it in play, and the more difficult it is for an opponent to return the ball. Wood racquets allowed players to only impart a modest amount of topspin, which limited the speed with which they could hit the ball. Composite racquets greatly increased the amount of topspin a player could impart, allowing players to hit more powerful and penetrating shots. Physicist Rod Cross (2006) provides a numerical example to illustrate why

---

[4]Figure 2 represents the most comprehensive data we could find on racquets used by individual players.

[5]Armstrong, Scott. "Technology Tugs at Tennis Traditions." *Christian Science Monitor.* 6 September 1983.
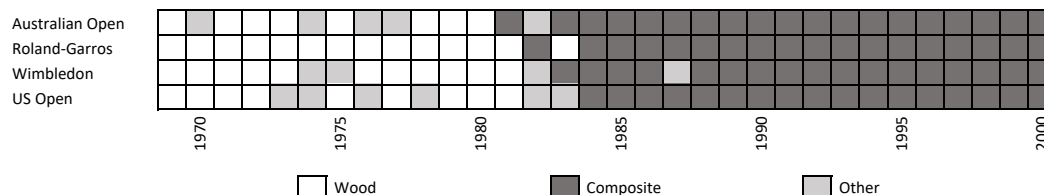
Figure 2: Racquet type used to win each Grand Slam over time

composite racquets had such a large effect on how the game is played.

> When a ball bounces off the court it acquires topspin, even if it had no spin before it hit the court. In fact, it spins faster than most players can generate themselves when they hit a topspin return. In order to return the ball with topspin, a player needs to swing the racquet both forwards and upwards and fast enough to reverse the rotation of the spinning ball. …

> Suppose, for example, that the ball spins at 3,000 rpm (50 revolutions/sec) after it bounces off the court. That is a typical amount of spin when a ball hits the court at around 30 or 40 mph. Returned with a wood racquet, a player won't be able to swing up at a very steep angle without clipping the frame. He will still be able to reverse the spin, but he will get only 200 rpm or so of topspin by swinging the racquet upward fairly rapidly at about 20 degrees to the horizontal. A change in spin from 3,000 rpm backwards to 200 rpm forwards is a change of 3,200 rpm, which is a relatively big change, but it is only enough to return the ball with a small amount of topspin.

> Now suppose the player switches to a 10-inch-wide racquet and swings up at 30 degrees to the ball. The player can do that and can also tilt the racquet head forward by about 5 degrees, with even less risk of

clipping the frame than with a 9-inch-wide wood racquet being swung at 20 degrees with the head perpendicular to the ground. In this way, the player will be able to change the spin by about 4,000 rpm instead of 3,200 rpm, with the result that the spin changes from 3,000 rpm of backspin to 1,000 rpm of topspin. The result is therefore a factor of five increase, from 200 rpm to 1,000 rpm, in the amount of topspin.

Although composite racquets allow players to generate much more topspin and power, taking full advantage of this potential required significant changes to players' strokes and play style. Older players in particular, who had invested years in learning to play with a wood racquet, faced the daunting challenge of adjusting to composite racquets. Players began altering their stances and swings to generate more topspin and power. They rotated their grips to generate more spin and help them return balls that were bouncing higher because of the increased topspin of their opponents. These seemingly subtle changes in technique and strategy resulted in a much more physical and faster-paced game. As Cross observed,

The modern game of tennis is played at a furious pace compared with the old days when everyone used wood racquets. Just watch old film from the 1950s and you will see that the game is vastly different. Ken Rosewall and Lew Hoad barely broke into a sweat. Today's game has players grunting and screaming on every shot, calling for the towel every third shot, and launching themselves off the court with the ferocity of their strokes.

3 Model

To guide our empirical analysis, we develop a model of skill-altering technological change. Since our theoretical results are intuitive, we give an overview of the model here and relegate details of the model to Appendix A. The model is a simple overlapping generations model in the spirit of MacDonald and Weisbach (2004). Each cohort consists of a mass one of players, each of whom live for three periods. We index periods with t and a player's age with a. A player's performance at age a

depends both on his skills and the current racquet technology. Let $\{x_{ia}, y_{ia}\}$ denote player i's skills at age a (these skills can be thought of as representing control and power/spin). Racquet technology r consists of the pair (A_r, λ_r), and a player's quality q_{iar} using racquet technology r is:

$$q_{iar} = A_r x_{ia}^{\lambda_r} y_{ia}^{1-\lambda_r}$$

so that

$$\log q_{iar} = \log A_r + \lambda_r \log x_{ia} + (1 - \lambda_r) \log y_{ia}.$$

Changes to parameters A_r and λ_r affect players differently. Parameter $\lambda_r \in (0, 1)$ controls the relative importance of skill x when using that racquet. A technology shock that decreases (increases) λ_r helps players who have relatively more (less) of skill y, while an increase in A_r increases quality for every player.[6]

Players' skills evolve over time in response to players' choices of which skills they invest in. Players are identical at birth.[7] During every period, each player selects the optimal technology for his skill composition and chooses how much to invest in each skill, subject to a budget constraint that depends on his age and a random shock. We assume that a player's quality, in expectation, grows over his career and is concave. Heterogeneity in player quality arises over time since those who receive favorable shocks end up with greater quality than those who do not.

A player's earnings depend on his quality and the market price for quality, which is a weakly decreasing function of the total quality of active players. If a player chooses not to play, he earns a wage w_0 and cannot rejoin the tour in the future.

Each period unfolds in the following order:

1. Players decide whether to play. Once he decides not to play, a player may not rejoin the tour later.

2. Players decide which racquet technology to use.

3. Players choose how to invest in their skills.

---

[6]However, player performance is zero-sum—every win for one player corresponds to a loss for another—and under the assumptions we make in Section 6, an increase in A_r for all players does not affect the probability that one player defeats another.

[7]See Appendix Section C for a discussion about allowing heterogeneous initial skills.

4. Players receive their wage if playing or the outside option w_0 if not playing.

Players choose whether to play, which technology to use, and how to invest in their skills to maximize their expected lifetime earnings.

4 Effect of introducing a new racquet technology

We use our model to understand how players are affected by the skill-altering technical change induced by the introduction of composite racquets. For notational simplicity, we drop the r subscript and denote variables related to the new racquet (i.e., the composite racquet) using a prime (i.e. λ' vs λ). Without loss of generality, we assume $\lambda > .5$. We model the introduction of composite racquets as a new technology with $A' > A$, so that the racquet is better overall, and $\lambda' < \lambda$, so that it shifts weight away from x, the previously technologically-favored skill. We assume A' is sufficiently larger than A such that all players switch in the same period.[8] The model offers three predictions to take to the data. We begin by characterizing how the new racquet changes player quality.

Lemma 1. *Switching to a new racquet induces a one-time change in a player's log quality of u_{ia}, where*

$$u_{ia} = \log A' - \log A + \left(\lambda' - \lambda\right)\left(\log x_{i,a-1} - \log y_{i,a-1}\right). \tag{1}$$

Lemma 1 shows that the magnitude of the change in player quality, u_{ia}, depends on the nature of the technological shock, with the magnitude increasing in both $A' - A$ and $|\lambda' - \lambda|$. This change varies across players and depends on a player's mix of skills x and y. A player with relatively more of the skill on which the new racquet puts additional weight, so $\log x_{i,a-1} - \log y_{i,a-1}$ is relatively small, experiences a

---

[8]As discussed in Section 2, the actual shift occured over a few years. Relaxing the assumption that A' is sufficiently larger than A so that all players switch does not change the results, as it simply truncates the distribution of changes in player quality (the soon-to-be-defined u_{it}) at zero. Thus, the magnitude of changes would be different, but which players are helped and hurt, and the consequences of this, are not.

larger u_{ia} and sees his quality relative to other players increase. Likewise, a player with relatively less of this skill experiences a smaller u_{ia} and sees his relative quality fall.[9]

4.1 Shock hurts better players

Since players targeted their prior investments to the mix of skills that was optimal for the old racquet, the new racquet helps lower quality players, who have not invested as much (either due to being younger or receiving smaller random shocks), more than it helps better players who have. The following proposition demonstrates this formally.

Proposition 1 (Shock hurts better players). *If player i was better than player j in the prior period $\left(i.e., q_{i,a_i(t-1)} > q_{j,a_j(t-1)}\right)$ then a technological shock that shifts weight away from the favored skill reduces the quality of player i relative to that of player j $\left(i.e., u_{ia_i(t)} < u_{ja_j(t)}\right)$.*

Because the technological shock hurts better players, it leads to a "reshuffling" of which players are good and which are not. Thus, a directly testable corollary to Proposition 1 is that the technological shock reduces the probability that a player who was better than another in the last period continues to be better, thereby reducing the period-to-period rank correlation of player quality.

Corollary 1 (Rank correlation falls). *A technological shock that shifts weight away from the favored skill temporarily reduces the rank correlation, as measured by Kendall's τ, in player quality over time.*

4.2 Younger players gain relative to older players

The technological shock, on average, benefits younger players at the expense of older players. It helps younger players because they have not spent their periods of skill acquisition acquiring the "wrong" mix of skills. Figure 3 illustrates the

---

[9]For players to want to switch, it must be that switching improves their quality, so $u_{ia} \geq 0$. This is the case if, for instance, A' is sufficiently larger than A.

evolution of player quality over time and how the effect of the new racquet varies by player age, where α_a denotes the expected increase in quality at age a. Player quality climbs over time, but when the new racquet arrives it helps those who begin their careers immediately after its arrival much more than it helps older players. This gives younger players a relative advantage over more experienced peers and they generally perform better than expected for their age. We formally show this in the following proposition.
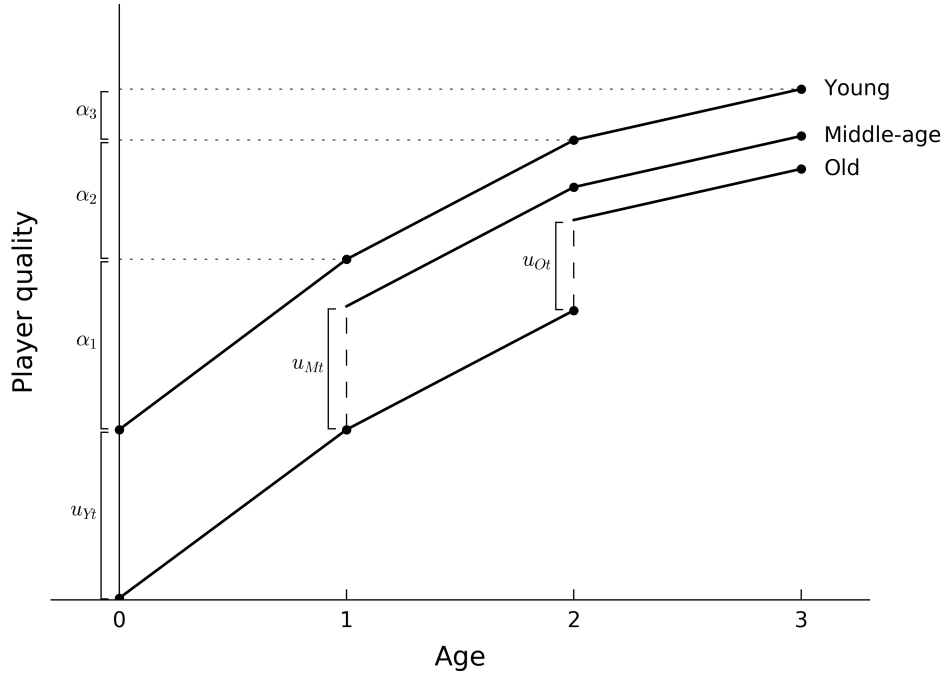

Figure 3: Change in quality trajectory when composite racquet technology arrives

Notes: "Young" players are in their first period when the new racquet arrives. "Middle-aged" and "old" players are in periods two and three of their careers when the new racquet arrives. The quality trajectories are shown with all shocks set to zero, so α_a is the (expected) increase in quality at age a and u_{it} is the change in quality due to the new racquet.

Proposition 2 (Shock hurts older players on average). *Suppose player i is older than player j when the new technology arrives, and that we were in a steady state before*

the new technology. Then a technological shock in period t that shifts weight away from the favored skill more likely than not reduces the quality of player i relative to the quality of player j. That is, $\mathbb{P}\left[u_{ia_i(t)} < u_{ja_j(t)}\right] > .5.$

Corollary 2 (Intergenerational inequality increases). *A technological shock that shifts weight away from the favored skill increases inequality between those who were old and those who were young at the time of the shock.*

Corollary 2 extends the logic of Proposition 2 to player cohorts. A skill-altering technical change increases intergenerational inequality by harming older players while helping younger players. Older players who invested for years in the hope of working their way to the top of the profession find that their investments are not worth as much, while younger players discover that they can compete at the top of the profession from the start of their career.

4.3   Exit rates

Since older players have been hurt relative to younger ones, it seems reasonable to conjecture that older players retire sooner while younger players exit less often. However, the new technology has an ambiguous effect on exit rates. To see why the effect on exit rates is ambiguous, consider an old player who is on the margin of exiting at the time of the technological shock. If the demand curve for his output is perfectly elastic, such that the price he receives per unit of quality is unchanged by the new technology, then his earnings are higher,[10] and he now strictly prefers to continue playing tennis. Thus, the exit rate for old players decreases. Now consider another extreme scenario in which demand is not perfectly elastic but $\lambda = 1$ and $\lambda' = 0$. That is, the technological shock completely devalues all investments the older player made and his quality is now equal to that of the youngest players. Hence, his expected earnings that period are the same as that of a young player. However, a young player is willing to earn less than w_0 because he expects his quality and earnings to grow in the future. Thus, the old player expects to earn less than w_0 and strictly prefers to exit instead. The following proposition states this ambiguity formally.

---

[10]His earnings are higher since his own quality has risen.

Proposition 3 (Ambiguous effects on exit rates). *A technological shock that shifts weight away from the favored skill can either increase or decrease the exit rate of older players.*

4.4   Cross-sectional inequality

Finally, skill-altering technical change has an ambiguous effect on cross-sectional inequality. By Proposition 1, the shock hurts better players relative to worse ones, implying that, holding fixed the set of players, the technological shock decreases cross-sectional inequality. However, the introduction of the composite racket also affects entry and exit decisions. If the new technology increases the entry rate of young players and the exit rate of older players, it might hollow out the skill distribution, thereby increasing cross-sectional inequality. Thus, a skill-altering technical change has an ambiguous effect on cross-sectional inequality.

4.5   Summary

In summary, this simple model of skill-altering change guides us when measuring the effect of the introduction of composite racquets on four outcomes in the data. First, the model predicts the new racquets will temporarily reduce the rank correlation in player quality over time. Second, the model predicts the new racquets will help younger players relative to older ones. Third, although it appears intuitive that the arrival of composite racquets would cause older players to retire at higher rates, the theoretical effect is ambiguous, leaving the effect of composite racquets on exit an empirical question. Finally, the model makes an ambiguous prediction about the effect of the new technology on cross-sectional inequality. We test these predictions using data on the universe of men's professional tennis matches.

5   Data

To test our theoretical predictions of the effect of a skill-altering technical change on players, we obtained data on all men's professional tennis matches played between

1968 and 2014.[11] The data were provided by the ATP World Tour, the governing body of men's professional tennis. For each match, we observe the winner and loser of the match and the score. The data also contains background information about players such as date of birth. Although the data contains information about tournament prize money, this data is incomplete prior to 1990. We use data from all main draw matches at Grand Slams, regular Tour events, Davis Cup, and the Challenger tour.[12] All these events award ATP ranking points, which determine a player's official ranking, and therefore eligibility for, and seeding in, future tournaments.[13]

We only include players who appear in the strongly connected component (SCC) for that year, essentially limiting analysis to those who both won and lost at least one match during a calendar year.[14,15] Although the SCC could be quite small in principle, in practice it contains the majority of players in the data and the vast majority of matches.[16] Defining active players as those in the strongly connected component has the practical effect of eliminating players who compete in a very small number of matches—on average, just 1.6 matches. These are typically young

---

[11]Women's professional tennis is governed by the Women's Tennis Association (WTA) which is independent of the ATP. Although the ATP and WTA are comparable in size and popularity today, during the 1970s the WTA was significantly smaller than the ATP. Therefore, we focus on men's professional tennis.

[12]We exclude qualifying rounds because we do not have data on them prior to 2007. We also exclude matches from the International Tennis Federation's Satellite and Futures tournaments because of incomplete data; these events are the lowest level of events which award ATP ranking points (i.e., they award the fewest number of ranking points and the least amount of prize money).

[13]"What is the Emirates ATP Rankings?" ATP World Tour, accessed 26 September 2016, http://www.atpworldtour.com/en/rankings/rankings-faq.

[14]More precisely, think of all the players in the data as points in a directed graph. Player i is connected to player j by a (directed) edge if i defeated j and vice versa. The SCC is the maximal subgraph of this directed graph such that, for any two players i and j in the SCC, there exists a directed path from i to j and from j to i.

[15]Table D.2 summarizes the win-loss records of excluded player-years, showing that 82% of player-years are dropped due to having no wins. Only 1.7% of player-years excluded from the SCC are dropped because they have no losses. These are due to instances where a player won a few matches, or even a tournament, but did not compete in any other events for the remainder of the year. This could happen if the player was injured, broke through on the tour at the end of the year, or qualified for only a single tournament, which he won, but did not qualify for any more events that year. For example, Wayne Arthurs played in only a single ATP tournament during 1997 due to an elbow injury. He won the tournament and as a result of his perfect win-loss record, is not included in the SCC for 1997.

[16]A match appears in the SCC only if both of its players are in the SCC.

players who are actively competing in lower level (non-Tour) events in the hope of becoming a regular competitor on the Tour, but who have not yet been able to make more than one or two Tour appearances. Limiting analysis to the strongly connected component reduces the number of player-years in the sample by 44 percent but reduces the number of matches by only 9 percent. Figures 4a and 4b show the number of matches and players in the SCC over time, Figure 4c shows how the number of tournaments has grown. Figure 4d shows that, other than for 1968 and 1969, the fraction of data in the SCC is consistent over time. Given limited data for 1968 and 1969, we omit these years from our analysis.[17]
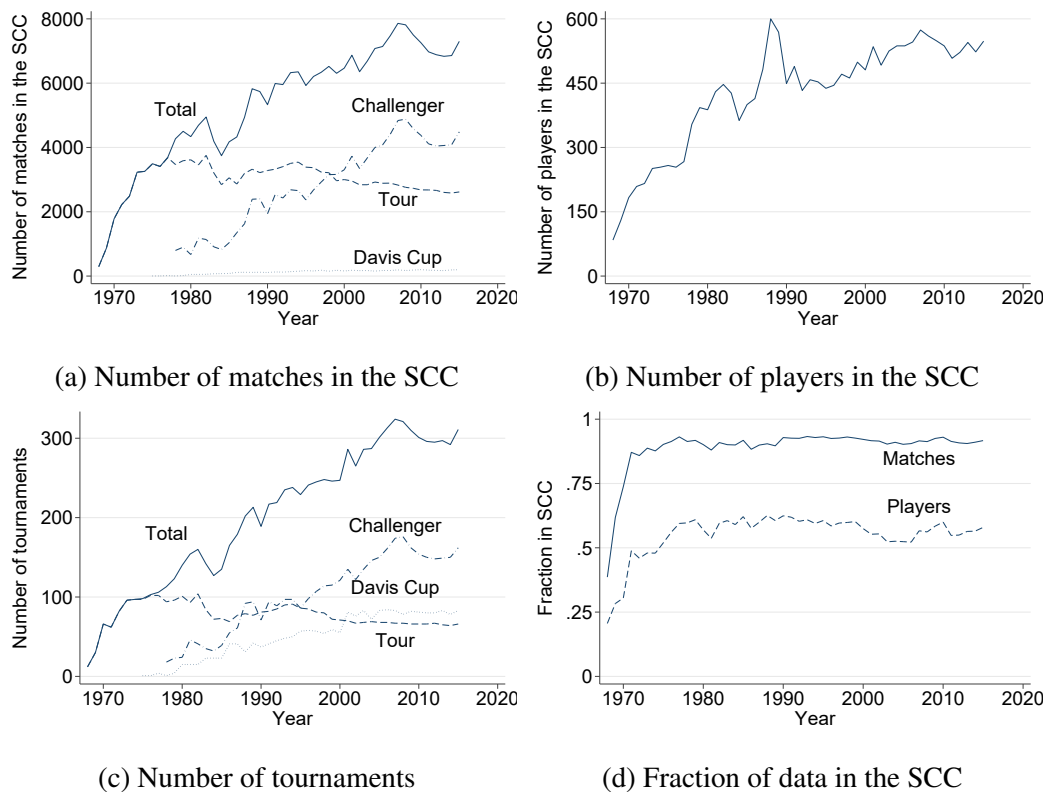

(a) Number of matches in the SCC

(b) Number of players in the SCC

(c) Number of tournaments

(d) Fraction of data in the SCC

Figure 4: Trends in tour size over time

Professional tennis players are typically between the ages of 18 and 35. Most

---

[17]Professional and amateur tennis officially merged in 1968, known today as the beginning of the Open Era. However, the transition took a few years and was not complete until about 1970. This is likely why the data is more limited prior to 1970.

professionals begin their careers around age 20, and few careers last more than 15 years (see Figure 5). Shown in Table 1, the average career consists of about six active years of play.
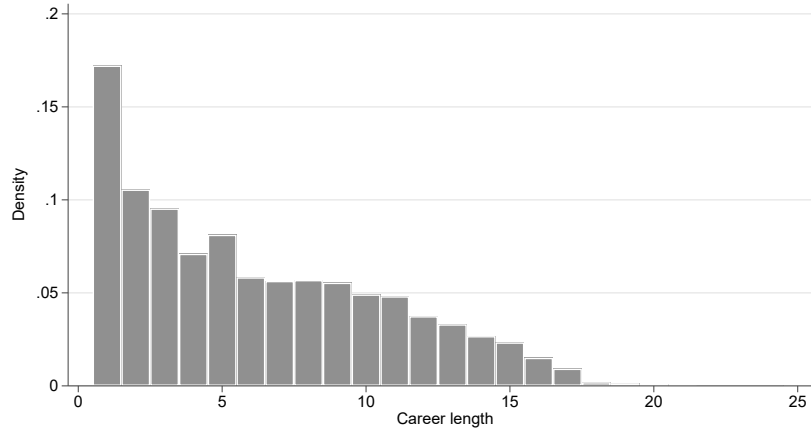

Figure 5: Histogram of number of years active on the tour

Table 1: Career summary statistics

	Mean	Median	Std. dev.
Age of entry	20.7	20.4	2.69
Number of years active	6.12	5	4.53
Career singles wins	87.1	29	130.6
Career singles matches	167.0	69	218.0
Observations	2541		

Notes: These summary statistics are calculated only for years in which a player appeared in the strongly connected component, but include all of their wins and matches during those years, regardless of whether their opponents were in the strongly connected component. The table is limited to players born between 1950 and 1985 so that we have had a chance to observe (nearly) all of their career.

Table 2 shows that the typical player plays only 26 matches per year, though this variable has a large right tail. The tail arises because, unlike many other sports in which teams play a fixed number of games during a season, tennis players compete in a tournament format. The tournament format causes more successful players to play many more matches than others during a year. To illustrate, consider a

Table 2: Player-year summary statistics

	Mean	Median	Std. dev.
Age	24.3	23.8	4.09
Annual singles wins	13.6	9	13.9
Annual singles matches	26.1	21	21.1
Observations	20275		

Notes: These summary statistics are calculated only for player-years in the strongly connected component, but include all of their wins and matches, regardless of whether their opponents were in the strongly connected component.

tournament with 64 players. Half will lose in the first round and therefore play only one match. At the other extreme, the winner and runner-up of the tournament will each play 6 matches. Since the best players are invited to more tournaments, this effect compounds during a year so that the best players play many more matches than the typical player.

The tournament format also complicates the interpretation of statistics, such as a player's win rate. In sports with a fixed number of games per season, a team's win rate provides a reasonable measure of success. In this case, win rates average 50 percent by construction, making them a useful benchmark for distinguishing winning and losing records. In tennis, the win rate is much more difficult to interpret. Returning to the example of a 64 player tournament, half of the players have a win rate of zero, one-quarter have a win rate of 50 percent, and so on, so that the average win rate among all 64 players is 30.7 percent. Thus, in any tournament the average tennis player has a "losing record," and only the top quarter of players have win rates in excess of 50 percent.

6 Estimating player quality

For estimation, we model player i's performance in match m as

$$\log \hat{q}_{im} = \log q_{it} + \mu_{im}$$

19

where q_{it} is i's quality in year t and μ_{im} is a type 1 extreme value match-specific shock. Since a given match takes place during a specific year, we let the match subscript absorb the time subscript. Player i wins a match against player j if, and only if, he performs better in the match: $\hat{q}_{im} > \hat{q}_{jm}$. Thus the probability that player i defeats player j in a match played in year t is given by the familiar logit expression

$$\mathbb{P}(i \text{ defeats } j) = p_{ijt} = \frac{q_{it}}{q_{it} + q_{jt}}, \tag{2}$$

and the likelihood of observing the data given these probabilities is:

$$L = \prod_{i=1}^{N} \prod_{j=i+1}^{N} p_{ijt}^{w_{ijt}} (1 - p_{ijt})^{w_{jit}}$$

where w_{ijt} is the number of times i is observed defeating j during year t. We use data on match outcomes to estimate each player's quality during each year, q_{it}, by choosing q_{it} to maximize this likelihood.

Players do not compete against a random sample of opponents, both because better players participate in more competitive tournaments and because as a player advances in a tournament he competes against increasingly better opponents. Simply calculating the fraction of matches won does not consider that players with more matches tend to play those matches against better opponents. For example, consider two players and two tournaments. Player A wins his first two matches at the first tournament but loses in the third round. He then loses in the first round of the second tournament, giving him a win rate of one-half. Player B makes it to the second round of the first tournament but is not invited to the second tournament, giving him the same win rate of one-half. Although A and B both won half of their matches, A's wins were against better opponents than B's, and the conditional logit model described above accounts for this when estimating their qualities. However, none of our theoretical predictions rely on the conditional logit assumption; we assume this to allow us to estimate player qualities from the data.

A player's quality is identified only if he is in the strongly connected component, which means he must have both won and lost to another player in the strongly connected component. This is necessary because if a player never won a match,

20

then to maximize the likelihood, we need to set his probability of winning to zero by setting his quality to 0. Likewise, if a player never lost a match, we need to set his probability of winning to one by setting his quality to infinity. A logit model cannot assign a finite (log) quality to these players, so we remove them. We iterate this process until no more players are removed. We define the remaining players as *active* and these are the players we use in our estimation.[18]

Our estimates of player quality within each year are only relative to other players within that year, because the probability that one player defeats another is unchanged if we add a constant to both players' (log) qualities. Thus, we normalize the estimates of (log) quality in a year to have a mean of zero, so the estimates must always be interpreted relative to the "average" player that year. This implies that, by construction, any trend in average quality has been removed.

7 Results

7.1 Returns to height rose

We have argued that composite racquets did not simply make all players better; rather, they shifted the relative returns to different skills. To test this claim, we would ideally use data on players' latent skills along with their performance to estimate the return to different skills in each year. Then we could observe whether those returns changed when composite racquets were introduced. While we cannot observe a player's latent skills, such as control or power, we do have data on a player's height which should be positively correlated with his power. Height is a fixed characteristic of players, so we do not need to be concerned about players endogenously adjusting their heights due to the new technology.[19]

Figure 6 plots the regression coefficient from regressing a player's (log) quality on his height in each year. The dashed lines mark the years when professional tennis players were transitioning to composite racquets. Prior to the introduction of

---

[18]This approach is essentially the same as that of Sorkin (2018).

[19]However, in the longer run there might be a response on the extensive margin as taller players become more likely to enter the tour.

the racquets, height appears to have conferred a *disadvantage*.[20] After composite racquets arrived, the returns to height reversed and taller players, who are better able to exploit the power and spin the racquets offer, have had an advantage ever since.

Figure 6: Relationship between estimated player (log) quality and height over time

Notes: The figure plots the regression coefficient from regressing a player's (log) quality on his height (in inches) in each year (circles) and a four-year lagged moving average (solid line). The dashed lines mark the years during which professional tennis players were transitioning to composite racquets. The figure reports the p-value of a t-test of whether the return to height before 1978 differed from the return between 1985 and 1999.

7.2   Year-to-year rank correlation of player quality fell temporarily

The first prediction from our model is that the transition from wood to composite racquets reduced the year-to-year rank correlation in player quality. Thus, we expect the change in technology to lead to a reshuffling of players since the new technology devalued better players' skills. Figure 7 verifies that this prediction holds in the data. For each year, we calculate the rank correlation (Kendall's τ) between a player's estimated quality from one year to the next.

---

[20]Lack of topspin forced players to make contact with a ball that was relatively low to the ground, which would have been more difficult for taller players.

As expectd, this correlation is positive—players with better ranks in one year tend to have better ranks in the next. This positive correlation rises over time, which may be due, in part, to increasing precision in our estimates of player quality over time due to players competing in more matches during later years. However, during the transition from wood to composite racquets, the rank correlation fell sharply before recovering to trend around 1990. We fit a regression to the data between 1970 and 1999 that allows for separate slopes and intercepts for three periods: pre-1978, 1978–1984, and 1985–1999. We then test this fit against a null hypothesis of a single slope and intercept over the entire period. This is a simple test for nonlinearity associated with the racquet transition. We reject the null hypothesis of a simple linear trend between 1970 and 1999 ($p = .012$).
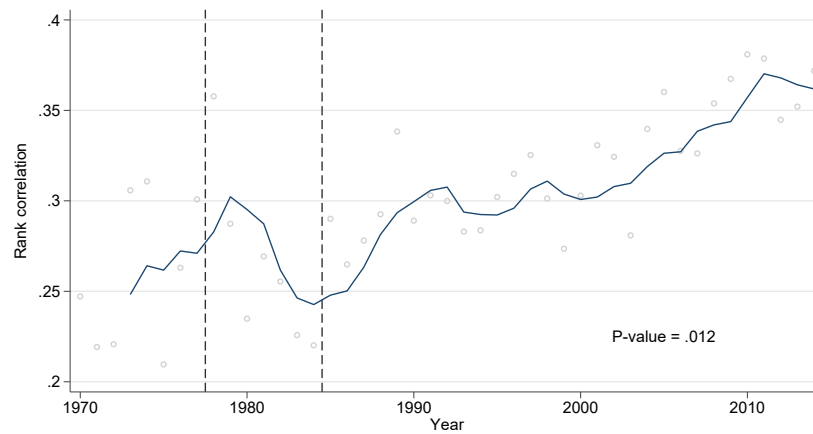

Figure 7: Year-to-year rank correlation of estimated player quality

Notes: This figure plots a measure of rank correlation (Kendall's τ) between a player's estimated quality in consecutive years (circles). If a player did not appear in year t but did in year $t-1$ or $t+1$, we imputed their quality to be below the minimum in year t. The solid line plots a four-year lagged moving average. The vertical dashed lines mark the years of the racquet transition (1978–1984). The reported p-value corresponds to an F-test for whether the pre-1978, 1978–1984, and 1985–1999 periods have the same slopes and intercepts.

7.3 Younger players gained relative to older players

Our model's second prediction is that the transition from wood to composite racquets should help younger players relative to older players. We test this in five ways. First, as Figure 8 shows, the average age of the top 16 players at Grand Slam events fell after the introduction of composite racquets.[21] The figure reports the p-value from an F-test for whether the slopes and intercepts are the same for the pre-1978, 1978–1984, and 1985–1999 periods. The results suggest that right after composite racquets arrived, there was a reduction in the age of players at the highest levels of play. This reduction was not permanent; the average age in 2015 was as high or higher than it was in the 1970s.[22]
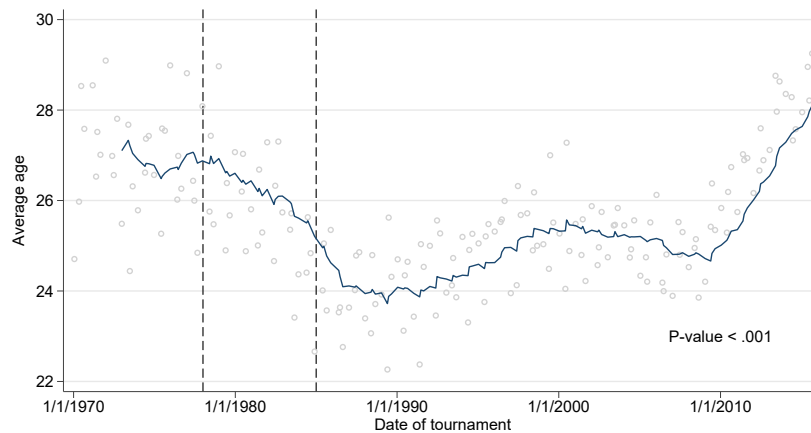
Figure 8: Average age in round of 16 of each Grand Slam over time

Notes: The figure plots the average age in the round of 16 for each Grand Slam (circles) and the average of the last three years of tournaments (solid line). The vertical dashed lines mark the years of the racquet transition (1978–1984). The p-value corresponds to an F-test for whether the pre-1978, 1978–1984, and 1985–1999 periods have the same slopes and intercepts.

Second, we show that the new racquets helped younger players relative to older players by examining the number of appearances in the round of 16 of a Grand Slam

---

[21] In men's tennis, the four Grand Slam events are the Australian Open, Roland-Garros, Wimbledon, and the U.S. Open.

[22] There is a steep rise in age after 2010, however it occurs many years after the transition period we are assessing. The rise might be attributable to innovations in physical training and health that allow players to extend their careers.

tournament by five-year birth cohort. In Figure 9, we plot the cumulative number of appearances made by members of that cohort in the round of 16 of a Grand Slam tournament. The 1950–1954 cohort were in the prime of their careers during the 1970s, before the new racquets arrived. The next cohort (1955–1959), however, was between 21 and 25 years old in 1980, so they were in the prime of their careers during the racquet transition. Compared to the prior cohort, the 1955–1959 cohort accumulated far fewer appearances—about 200 appearances compared to about 350 for the 1950–1954 cohort. Moreover, while the 1955–1959 cohort begins normally, their appearances reach an abrupt plateau right at the end of the transition period. Subsequent generations performed increasingly better, culminating in the 1970-1974 cohort who were between 6 and 10 years old in 1980, so they were the first cohort to learn to play tennis with the new racquets. As a result, they accumulated over 400 appearances, more than any cohort before or since.[23] In Table 3, we calculate the age at which each cohort reached different milestones, finding that the 1970–1974 cohort reached these milestones about two years before the typical cohort, while the 1955–1959 cohort reached 200 appearances nearly a decade late.

We do not observe prize money prior to 1990, so we put these effects in dollar terms using data after 1990 to regress a cohort's log prize money during year t on its log number of round of 16 appearances during year t. We estimate an elasticity of 1.2, so a ten percent increase in a cohort's round of 16 appearances correlates with a 12 percent increase in prize money.[24] Thus, the 1955–1959 cohort earned about 50 percent less career prize money than the prior cohort and more than 60 percent less than the 1970–1974 cohort.[25] By estimating cohort earnings, we capture both lost prize money of those who exit and lower prize money for those who continue playing.

Third, younger players' increased their share of matches across the tour, and this increase came at the expense of older players. As Figure 10 shows, players between

---

[23]It also appears that the next cohort, 1975–1979, was adversely affected by the dominance of the 1970–1974 cohort. It seems plausible that the dominant 1970–1974 cohort effectively locked the following cohort out of opportunities on the tour.

[24]For full regression results, see Table D.3 in the appendix.

[25]These calculations do not incorporate non-prize earnings players might have received while playing or after exiting the tour.
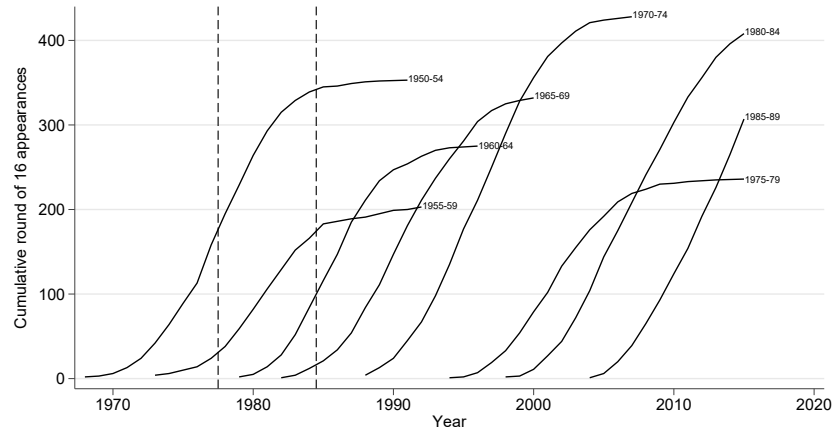
Figure 9: Grand Slam performance by birth cohort

Notes: The figure plots the cumulative number of Grand Slam round of 16 appearances for each five-year birth cohort.

Table 3: Age at which each birth cohort achieved a given number of round of 16 appearances in Grand Slams

| | Round of 16 Appearances | | | |
	150	200	250	300
1950-54	26.8	28.1	29.6	31.3
1955-59	27.9	36.0	.	.
1960-64	26.1	27.6	30.4	.
1965-69	25.1	26.6	28.6	30.8
1970-74	24.4	25.7	27.0	28.3
1975-79	27.8	30.5	.	.
1980-84	25.2	26.8	28.3	29.9
1985-89	25.9	27.2	28.6	29.8
Median	26.0	27.4	29.1	31.1

Notes: For cohorts that never reached a given number of appearances, the cell is marked with a dash. The last row reports the median of all eight cohorts, treating missing cells as infinite.

ages 18 and 21 double their share of matches from less than 20 percent during the mid-1970s to over 30 percent by 1990. This increase came at the expense of older players, ages 26 to 39, with the most severe reductions appearing among players over 30. Starting during the 1990s, younger players accounted for a diminishing share of matches, returning to less than 20 percent by 2015, while the share of older players recovered, ultimately returning to its previous level. For young and old players, we reject the hypothesis of a simple linear trend between 1970 and 1999.
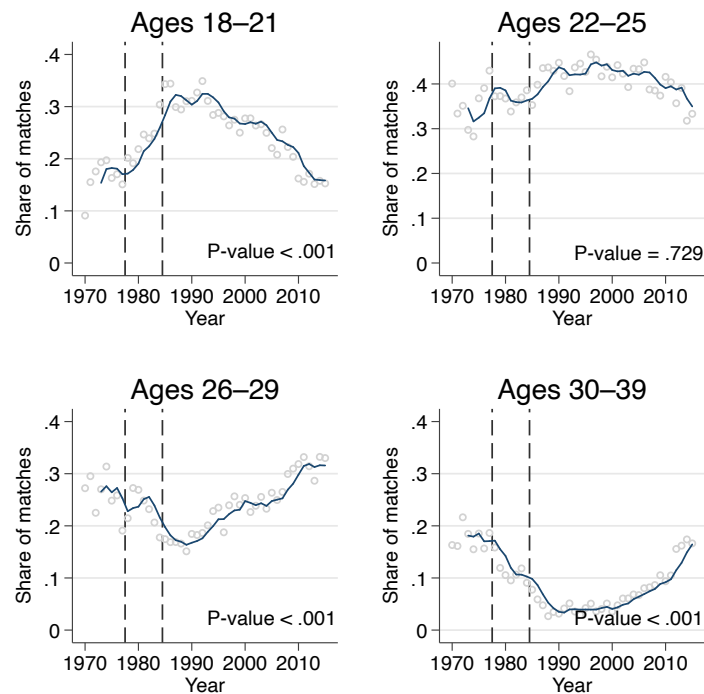

Figure 10: Share of matches by age group over time

Notes: The figure plots the share of matches by age group for each year (circles) and a four-year lagged moving average (solid line). The vertical dashed lines mark the years of the racquet transition (1978–1984). The p-value corresponds to an F-test for whether the pre-1978, 1978–1984, and 1985–1999 periods have the same slopes and intercepts.

The U-shaped (and inverted U-shaped) patterns suggest that the effect of the new composite racquets was temporary. It does not appear that the composite racquets,

by increasing the pace and intensity of play, made it impossible for older players to compete. Rather, the transition from wood to composite racquets temporarily disadvantaged older players because the skills they had spent their career investing in were no longer as valuable. These patterns show how long it took for professional tennis to respond to the introduction of composite racquets. Depending on the figure, it took until 2005 to 2010 for outcomes to return to the levels they were at before composite racquets were introduced. Thus, the transition in response to the new composite racquets lasted for nearly 25 years (1984–2010). If the average player has a career of about six years, then a 25-year transition corresponds to four generations of average professional tennis players. Because more successful players have longer careers (about 15 years), the transition lasted for nearly two generations of more successful players. The length of the transition is likely due to unmodeled factors, such as the time it takes to discover the optimal strategy to use with the new racquets and the time it takes to learn the ideal mix of skills that complemented the composite racquet. These estimates are similar in magnitude to those from Clark (2005), who estimates it took about 60 years for the technical innovations of the Industrial Revolution to lead to rising real wages.

Fourth, we use our estimates of player quality to show more directly younger players gained relative to older players. In Figure 11, we plot the median ages of players with above- and below-average (log) quality (i.e., $\log \hat{q}_{it} > 0$ and $\log \hat{q}_{it} \leq 0$ respectively). During the early 1970s, above-average players tended to be older than below-average players. During the racquet transition the median age fell for both groups, but it declined far more quickly for above-average players, so that for a few years during the mid-1980s the median above-average player was no longer older than the median below-average player. Over the next two decades, the median age rose for both groups, again rising more quickly for above-average players. These changes in the median age are even more dramatic when considering that the typical professional tennis player competes on the tour for only 6 years. Figure 11 reports the p-value from an F-test of whether the nonlinear trends of above- and below-average players were parallel between 1970 and 1999. We find that not only did the entire tour get temporarily younger after composite racquets arrived, but the age of higher-quality players fell even more than lower-quality players.
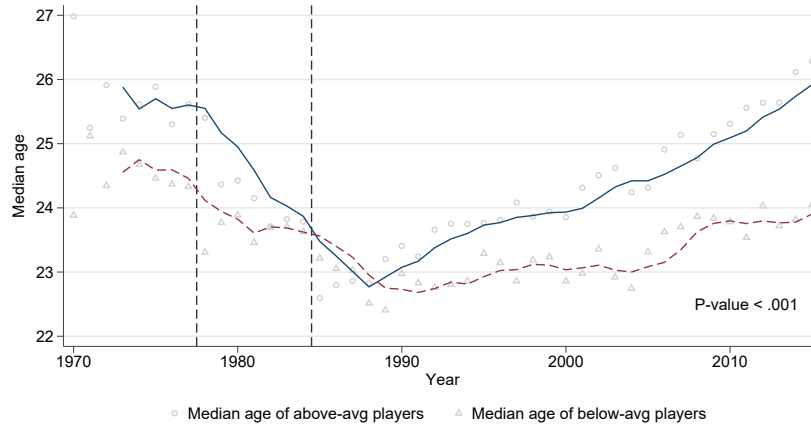
Figure 11: Median age of above- and below-average players over time

Notes: The figure plots the median age of above- and below-average players in each year (circles and triangles) and a four-year lagged moving average (solid and dashed lines). The vertical dashed lines mark the years of the racquet transition (1978–1984). The reported p-value corresponds to an F-test for whether above-average and below-average players have parallel trends between 1970 and 1999.

Fifth, Figure 12 plots the evolution of the age-quality gradient over time. As the model predicts, older players are typically better than younger players; one year is correlated with approximately 2.5 percent higher quality before 1978. This occurs both because older players have more experience, and because older players retire when they are no longer successful, while a younger player at the same level of quality might keep trying to improve. However, during the transition to composite racquets the correlation falls, and the point estimates even turn negative for a few years, before eventually recovering to their previous levels.

To put the changes in the age-quality gradient into dollar terms, we estimate the relationship between a player's estimated (log) quality and his (log) annual prize money. Since we do not have reliable data about prize money prior to 1990, we regress a player's (log) annual prize money on his (log) estimated quality using data pooled from the first five years available—1990 through 1994 (see Figure 13).[26]

---

[26]We exclude player-year observations with five or fewer matches and run a weighted regression, weighting each observation by the number of matches played. The rationale for weighting by number of matches is that players with more matches have more precisely estimated values for quality, thereby mitigating attenuation bias.

Figure 12: Correlation between estimated quality and age over time

Notes: The figure plots the age-quality gradient in each year (circles) and a four-year lagged moving average (solid line). The vertical dashed lines mark the years of the racquet transition (1978–1984). The p-value corresponds to an F-test for whether the pre-1978, 1978–1984, and 1985–1999 periods have the same slopes and intercepts.

We find that a ten percent increase in a player's estimated quality corresponds to an 11.4 percent increase in prize money. Assuming this elasticity between prize money and player quality has not changed over time, we can back out the implied OLS relationship between (log) prize money and age by:

$$\beta_{prize,age} = \beta_{prize,qual} \times \beta_{qual,age} = 1.14 \times \beta_{qual,age}$$

where $\beta_{y,x}$ denotes the OLS coefficient from regressing y on x. Figure 14 plots the implied OLS coefficient over time. Both before and after the racquet transition, being one year older correlates with three to five percent higher annual earnings. However, during the racquet transition, this age-earnings gradient temporarily disappeared.

7.4 Exit rates of older players rose relative to younger players

Our model does not make a clear prediction about how the exit decisions of older players respond to the technology shock. However, as shown in Figure 15, we find that exit rates rose during the racquet transition, most dramatically among older
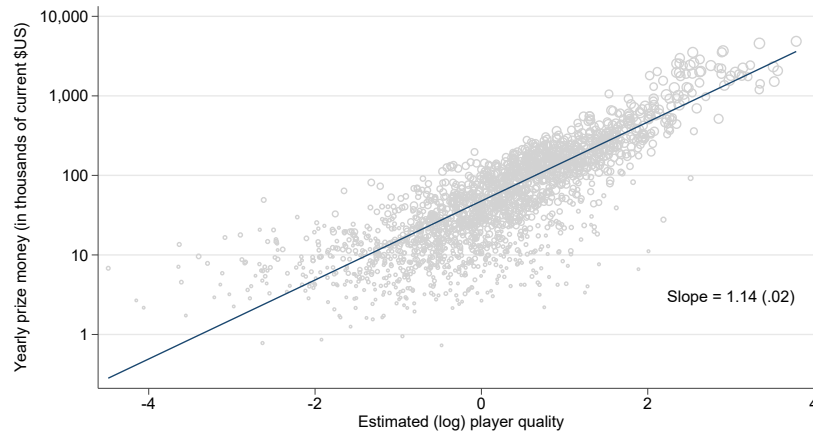
Figure 13: Estimated player quality and yearly prize money

Notes: The figure only includes data from 1990 to 1994 and players who played more than five matches during the year. The regression line and marker sizes are weighted by number of matches played.
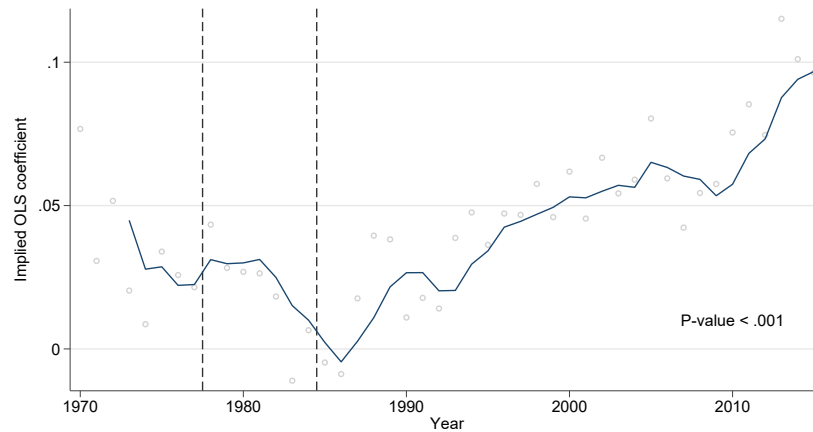

Figure 14: Implied age-earnings gradient

Notes: The implied age-earnings gradient in each year (circles) was calculated by regressing (log) estimated quality on age in each year and regressing (log) annual prize money on (log) estimated quality for the years 1990 to 1994. We then multiply these two coefficients together to obtain the implied OLS coefficient from regressing (log) annual prize money on age in each year (circles). The figure also plots a four-year lagged moving average (solid line). The p-value corresponds to an F-test for whether the pre-1978, 1978–1984, and 1985–1999 periods have the same slopes and intercepts.

31

players. We define an exit to occur whenever a player was active during year t but was not active during year $t + 1$.[27] During the racquet transition, the exit rates for players aged 22–25 and 26–29 rose approximately ten percentage points from 10 to 20 percent and from 20 to 30 percent, respectively. Although it began prior to the racquet transition, the exit rate for players aged 30–39 rose even more dramatically. Starting during the 1990s, however, the exit rates of players over age 25 declined, nearly returning to their previous levels.
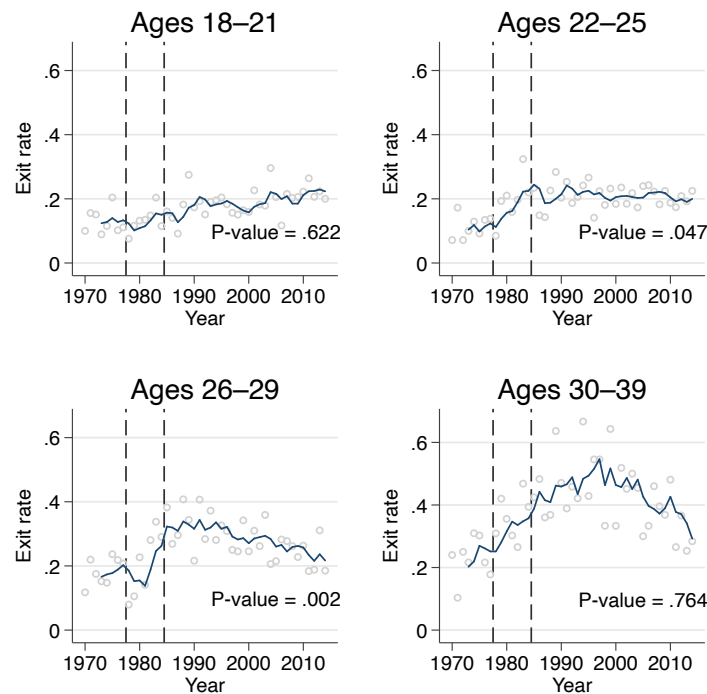
Figure 15: Exit rates by age group over time

Notes: The figure plots the exit rate by age group for each year (circles) and a four-year lagged moving average (solid line). The vertical dashed lines mark the years of the racquet transition (1978–1984). The p-value corresponds to an F-test for whether the pre-1978, 1978–1984, and 1985–1999 periods have the same slopes and intercepts.

---

[27] Although we rule it out in our model, this definition of exit implies that a player could exit (and re-enter) multiple times over his career. Twenty-nine percent of players exit and re-enter at least once, often due to injuries.

During the transition from wood to composite racquets, young players found it easier to enter the tour and be successful. In Figure 16, we plot the average age at which a birth cohort first entered the tour against the age of that cohort in 1980, when the tour was transitioning from wood to composite racquets. Recall that "entering the tour" means that a player is in the strongly connected component, so the age of entry we measure indicates the first time a player had a substantial presence on the tour. Players who were about 10 years old in 1980 entered the tour at an average age of 20, but both older and younger cohorts entered as much as a year and a half later. Notably, players who were 10 years old in 1980 were among the first who grew up playing with composite racquets.
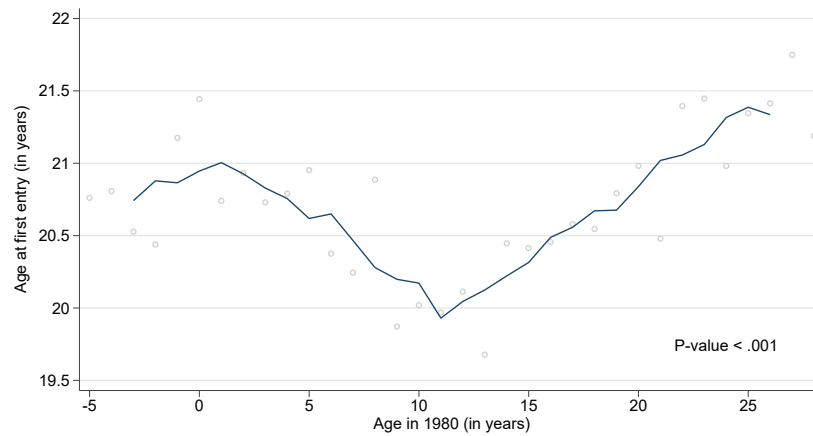

Figure 16: Age when first entered tour by age in 1980

Notes: The figure plots the mean age when a player first entered the tour for each birth year, reported as age in 1980 (circles) and a five-year centered moving average (solid line). The vertical dashed lines mark the years of the racquet transition (1978–1984). The p-value corresponds to an F-test for whether the trend for points to the left of 10 have a different intercept and slope than the trend for points to the right of 10.

The combination of increased exit rates for older players and earlier entry ages caused the age distribution of players on tour to compress and shift younger. Figure 17 plots the quartiles of the age distribution of all players on tour over time. During the late 1970s and early 1980s, the median age fell from 25 to 23, and the 75th percentile fell more dramatically, from 29 to 25. However, over time, the distribution

33

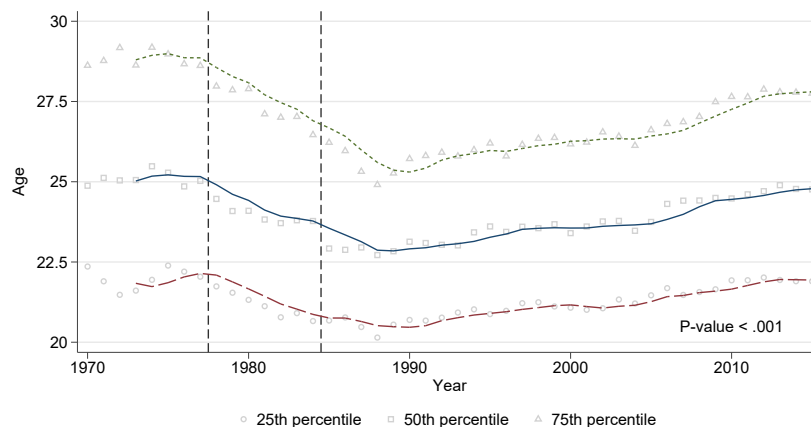shifted back toward older ages, with the median age returning to 25.

Figure 17: Age distribution over time

Notes: The figure plots the quartiles of the age distribution in each year, along with four-year lagged moving averages. The vertical dashed lines mark the years of the racquet transition (1978–1984). The p-value corresponds to an F-test for whether the pre-1978, 1978–1984, and 1985–1999 periods have the same slopes and intercepts for the median age.

7.5 Cross-sectional inequality during the transition

Finally, we examine two measures of cross-sectional inequality and find the results depend on the definition of inequality we use.[28] This is unsurprising since Section 4.4 shows that skill-altering technical change makes an ambiguous prediction about cross-sectional inequality. First, we plot the standard deviation of (log) player quality in each year. Figure 18 shows that the standard deviation of player quality dipped during the 1990s. However, we find the opposite for the second measure of cross-sectional inequality. For this measure, we count the number of unique players advancing to a given round of at least one Grand Slam tournament, and then divide by the total number of slots in that round. This ratio measures the degree to which success at Grand Slams is concentrated among a few players and ranges from 0.25

---

[28]Ideally, we would examine inequality in player earnings. However, data on prize money is unavailable prior to 1990.

(most concentrated) to one (least concentrated). For example, there are 64 slots available in the round of 16 across all four Grand Slam tournaments. If the same 16 players took those slots in each tournament, the ratio would be 0.25. At the other extreme, the ratio would be one if a completely different set of 16 players took the slots in each tournament. Whether we examine the round of 16, 32, or 64, we find that concentration was fairly constant until around 1984 when it began to rise (the ratio began to fall). The increase in concentration was most pronounced for the rounds of 32 and 64, which saw the number of players per slot decrease from 0.7 and 0.6 in 1980 to about 0.6 and 0.55 in the mid-1990s. Thus, even as the standard deviation of player quality decreased across the tour as a whole, Grand Slam success at the top of the tour became more concentrated among a smaller group of players.
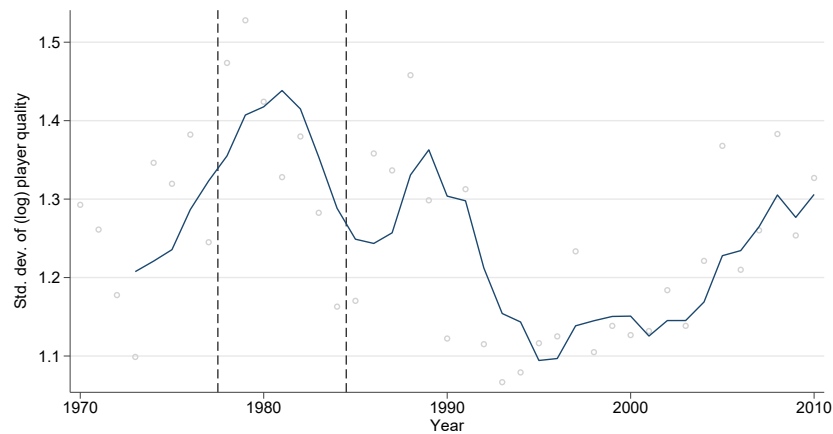
Figure 18: Cross-sectional standard deviation of player quality

Notes: The figure plots the standard deviation of (log) quality in each year, along with four-year lagged moving averages. The vertical dashed lines mark the years of the racquet transition (1978–1984).

8 Alternative explanations

We now address alternative explanations. First, some of our empirical results might be caused by the growth of the tour over time. For example, the entry of young
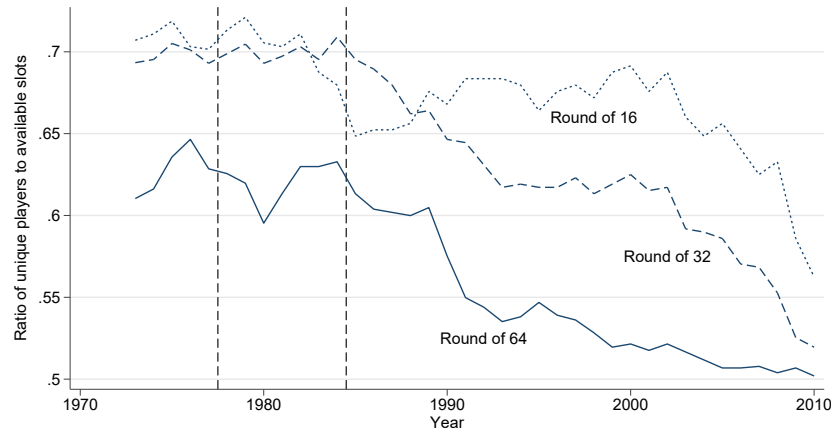
Figure 19: Concentration of Grand Slam success

Notes: The figure plots four-year lagged moving averages of the number of unique players who advanced to a given round in at least one Grand Slam event, divided by the number of slots in that round over the year. The lower this ratio, the more concentrated Grand Slam success is among a small number of players. The vertical dashed lines mark the years of the racquet transition (1978–1984).

players might have been caused by increased demand for new tennis players as the tour expanded. However, one problem with this explanation is that it would predict the exit rates of older players to fall, not rise.[29] This explanation also cannot account for the change in the returns to height, the reduction in the rank correlation of player quality and the age-quality gradient, and the poor performance of birth cohorts who were in their prime during the racquet transition. Still, we explore this possibility in Appendix E by repeating our analysis while limiting the sample to data from only Grand Slams. This provides a constant "tour size" in each year, though one drawback is that the Grand Slams do not contain enough matches to reliably estimate player quality. Moreover, by focusing on Grand Slams, our analysis is limited to the top players on tour. Nevertheless, we find similar qualitative patterns to those in our main analysis.

---

[29]Greater demand for professional tennis would lead to an increase in both the number of players and their wages, thereby reducing the exit rate of older players. The tour might have experienced a *supply* shock of young players, which would increase the number of players and push wages down, thereby raising the exit rate of older players. However, prize money rose over the transition period (see Figure D.1 in the online appendix), which rules out a supply shock.

Second, the changes we observe in tennis might be the result of broader changes to sports or the economy. To test this, we compare the ages of Olympic athletes over time to the ages of tennis players. We use data on male Olympic athletes who competed in events that existed during all summer Olympic games from 1960 to 2016, excluding tennis. Figure 20 shows that in comparison to professional tennis, the ages of Olympic athletes were stable over time. Prior to the introduction of composite racquets, tennis players were older than Olympic athletes, but by the end of the transition, that had reversed. In 1988, the median age of tennis players was 1.9 years lower than Olympians. But, between 1988 and 2012, the gap between tennis players and Olympians declined by nearly half to 1.0 years in 2012, and we see similar patterns at the 25th and 75th percentiles.
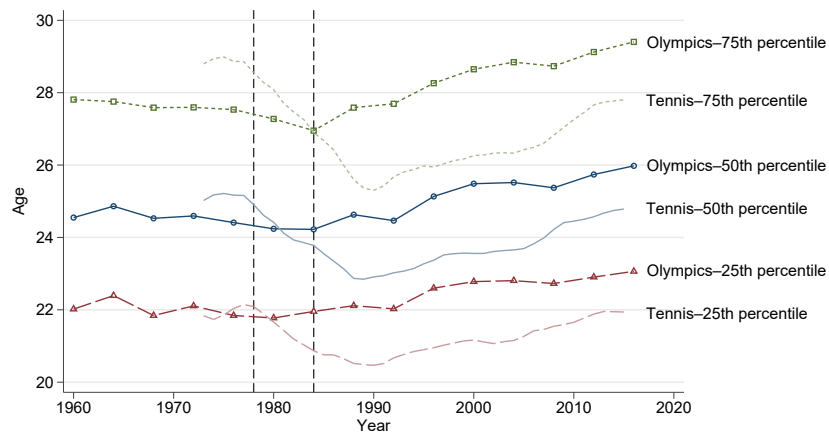
Figure 20: Age distribution over time: Olympics vs. tennis

Notes: This figure plots quartiles of the age distribution for male athletes in the summer Olympic games and the four-year moving average of quartiles of the age distribution from Figure 17. The set of Olympic athletes is restricted to those competing in events which existed in all summer Olympic games from 1960 to 2016, excluding tennis. The vertical dashed lines mark the years when professional tennis players were transitioning to composite racquets. The data on Olympic athletes comes from http://www.olympedia.org/.

37

9 Conclusion

We examine the effects of technological change in the context of a major innovation in men's professional tennis—the introduction of composite racquets during the late 1970s and early 1980s. We find that the introduction of composite racquets temporarily helped younger players at the expense of older players, reduced the rank correlation in player quality over time, and increased exit rates of older players relative to younger ones. Over time, these temporary shifts largely reversed, though the transition took two to four generations. These empirical findings are consistent with a model of skill-altering technological change.

Men's professional tennis provides an excellent setting for studying the effects of skill-altering technological change on workers for four reasons. First, we have detailed panel data on multiple cohorts of individual players. Second, the new technology arrived suddenly and unexpectedly and was universally adopted within a few years. Third, tennis careers are short—six years on average and rarely more than 15 years—which allows us to follow multiple cohorts of players over their entire careers. Fourth, since we can observe the performance of a player without worrying about the effects of teammates, professional tennis offers unusually clean measures of worker productivity.

While the magnitude of the effects we identify depend on the size of the technological shock (i.e., the change in λ), and so vary across settings, the qualitative effects likely manifest in other situations. As such, this episode in men's tennis provides insights into the effects of past and future technological innovation on workers. When a new technology arrives—whether tractors in farming, drafting software in architecture, or composite racquets in professional tennis—current workers find it difficult to adopt the new technology because their skills are adapted to the prior technology. Thus, although they may attempt to switch, they remain at a disadvantage to younger workers who have not spent valuable time learning to use the now-outdated technology. Older workers experience a relative decline in their productivity while younger workers receive a boost from being the first group of workers to take full advantage of the new technology. Although these effects are temporary, they persist for multiple generations of workers, with permanent

effects on middle-aged and older cohorts during the transition to the new technology. Moreover, the risks of future skill-altering technological change will reduce workers incentive to make human capital investments, especially investments in specialized skills.

References

Acemoglu, D. (2002). Technical Change, Inequality, and the Labor Market. *Journal of Economic Literature 40*(1), 7–72.

Akerman, A., I. Gaarder, and M. Mogstad (2015, jul). The Skill Complementarity of Broadband Internet. *Quarterly Journal of Economics 130*(4), 1781–1824.

Autor, D. H., L. F. Katz, and M. S. Kearney (2008). Trends in U.S. Wage Inequality: Revising the Revisionists. *Review of Economics and Statistics 90*(2), 300–323.

Binswanger, H. (1986). Agricultural Mechanization: A Comparative Historical Perspective. *The World Bank Research Observer 1*(1), 27–56.

Card, D. and J. E. DiNardo (2002). Skill-Biased Technological Change and Rising Wage Inequality: Some Problems and Puzzles. *Journal of Labor Economics 20*(4), 733–783.

Clark, G. (2005). The Condition of the Working Class in England, 1209–2004. *Journal of Political Economy 113*(6), 1307–1340.

Cross, R. (2006). The Inch That Changed Tennis Forever. *Tennis Industry Magazine* (January).

Flood, S., M. King, S. Ruggles, and J. R. Warren (2017). Integrated Public Use Microdata Series, Current Population Survey: Version 5.0. [dataset]. Minneapolis: University of Minnesota.

Gaggl, P. and G. C. Wright (2017). A Short-Run View of What Computers Do: Evidence from a UK Tax Incentive. *American Economic Journal: Applied Economics 9*(3), 262–294.

Gannaway, G., C. Palsson, J. Price, and D. Sims (2014). Technological Change, Relative Worker Productivity, and Firm-Level Substitution: Evidence from the NBA. *Journal of Sports Economics 15*(5), 478–496.

Hanssen, F. A. (2020). "What's Wrong With the Way I Talk?" The Effect of Sound Motion Pictures on Actor Careers. *Economic Inquiry 58*(1), 474–495.

Horton, J. J. and P. Tambe (2020). The Death of a Technical Skill. Mimeo.

MacDonald, G. and M. S. Weisbach (2004). The Economics of Has-beens. *Journal of Political Economy 112*(S1), S289–S310.

Ruggles, S., S. Flood, R. Goeken, J. Grover, E. Meyer, J. Pacas, and M. Sobek (2018). IPUMS USA: Version 8.0 [dataset]. Minneapolis, MN.

Sorkin, I. (2018). Ranking Firms Using Revealed Preference. *Quarterly Journal of Economics 133*(3), 1331–1393.

Appendices

Appendix A Model

A.1 Player skills and quality

This section gives the details of the model of skill-altering technological change we use to guide our empirical analysis in the paper. The model is a simple overlapping generations model in the spirit of MacDonald and Weisbach (2004). Each cohort consists of a mass one of players, each of whom live for three periods. We index periods with t and a player's age with a. Let s_i denote the period player i is "born," so that a player's age in period t is just $a_i(t) = t - s_i + 1$. A player's performance at age a depends both on his skills and how these skills combine with the current racquet technology. Let $\{x_{ia}, y_{ia}\}$ denote player i's skills at age a (these skills might be thought of as being control and power/spin). A racquet technology r consists of the pair (A_r, λ_r), and a player's quality q_{iar} using racquet technology r is given by

$$q_{iar} = A_r x_{ia}^{\lambda_r} y_{ia}^{1-\lambda_r}$$

so that

$$\log q_{iar} = \log A_r + \lambda_r \log x_{ia} + (1 - \lambda_r) \log y_{ia}.$$

Changes in the parameters A_r and λ_r affect players differently. The parameter $\lambda_r \in (0,1)$ controls the relative importance of skill x in using that racquet. A technology shock that decreases (increases) λ_r will help players who have relatively more (less) of skill y. Increases in A_r is an increase in total factor productivity and increases quality for every player. However, player performance is zero-sum—every win for one player corresponds to a loss for another player—and, under the assumptions we make in Section 6, an increase in A_r for all players will not affect the probability that one player defeats another.

A.2 Evolution of skill

Players choose an optimal mix of skill investment, and their skills evolve over time. Player i is born in period s_i with a common skill vector $\{x_0, y_0\} \in \mathscr{R}^2_+$.[30] At age a, he selects the optimal technology for his skill composition and improves his skills by $(\alpha_a + \varepsilon_{ia}) \left(\lambda_r^2 + (1-\lambda_r)^2\right)^{-1/2}$ units in the $\log x$–$\log y$ plane, where the shock ε_{ia} is mean zero and iid with distribution F and $\left(\lambda_r^2 + (1-\lambda_r)^2\right)^{-1/2}$ serves as a normalizing constant.[31] A player chooses the optimal direction of improvement in $\log x$–$\log y$ space, which amounts to setting the direction of improvement perpendicular to the isoquant of the racquet technology he is using. Note that, although players choose the *direction* of investment in skills, the amount of improvement is determined exogenously. This modeling assumption focuses attention on the player's choice of direction of investment, rather than the level of investment. These assumptions give us the following laws of motion for skills:

$$\Delta \log x_{ia} = \log x_{ia} - \log x_{i,a-1} = \frac{\lambda_r}{\lambda_r^2 + (1-\lambda_r)^2} (\alpha_a + \varepsilon_{ia}) \tag{3}$$

$$\Delta \log y_{ia} = \log y_{ia} - \log y_{i,a-1} = \frac{1-\lambda_r}{\lambda_r^2 + (1-\lambda_r)^2} (\alpha_a + \varepsilon_{ia}) \tag{4}$$

These skill-specific laws of motion imply that, in the absence of any changes in racquet technology, the player's overall quality evolves according to

$$\Delta \log q_{iar} = \log q_{iar} - \log q_{i,a-1,r} = \lambda_r \Delta \log x_{ia} + (1-\lambda_r) \Delta \log y_{ia}$$

$$= \alpha_a + \varepsilon_{ia} \tag{5}$$

We assume $\alpha_1 > \alpha_2 > \alpha_3 > 0$ so that a player's quality, in expectation, grows over his career and is concave. Heterogeneity in player quality arises over time because of the shocks ε_{ia}, since those who receive favorable shocks end up with higher quality

---

[30]See Appendix Section C for a discussion about allowing for heterogeneous initial skills.

[31]It is worth noting that our model does not allow for skills to depreciate. Earlier versions of the paper had this feature, but it added complexity without adding any additional insights we could test in our data. An additional theoretical insight from allowing skills to depreciate is that the larger the rate of depreciation, the less the effect of a technological shock. Taken to its extreme, if skills depreciate completely each period then the technological shock has no effect on players.

than those who do not.

A.3   Player quality and earnings

At the beginning of each period, a player must choose whether to play tennis *before* observing his shock. If a player plays tennis in period t, he earns $q_{ia_i(t)r} \cdot p(Q_t)$, where $Q_t = \sum_j q_{ja_j(t)r}$, $p(Q)$ is continuous and differentiable, and $p'(Q) < 0$.[32] If he chooses not to play, then he earns a wage w_0.

A.4   Entry and exit

Each period unfolds in the following order:

1. Players decide whether to play or not. If a player does not play, he receives a wage w_0. Once he decides not to play, he may not rejoin the tour later.

2. Players decide which racquet technology to use.

3. Players choose their direction of investment. The optimal investment depends on λ_r, the relative weight the racquet places on one skill over another.

4. Players receive their quality shocks ε_{ia} and their new qualities are realized
$$\log q_{iar} = \log q_{i,a-1,r} + \alpha_a + \varepsilon_{ia}.$$

5. The player, if he plays tennis, receives his wage $q_{iar} \cdot p(Q_t)$.

Players choose whether to play, which technology to use, and the direction of their investment to maximize their expected earnings. Recall that players only live for three periods.[33]

 The present value of a player's earnings when he is age a at the start of period t

---

[32]The summation in the expression for Q_t is over all players who are playing tennis in period t.

[33]Allowing for an arbitrary number of periods does not change our results.

is

$$V_a^t(q_{a-1}, \vec{z}_{t-1}) = \max \left\{ \underbrace{\mathbb{E}\left[q_a \cdot p(Q_t) + \beta V_{a+1}^{t+1}(q_a, \vec{z}_t) \mid q_{a-1}, \vec{z}_{t-1}\right]}_{\text{expected value of playing for one more year}}, \underbrace{\sum_{\tau=a}^{3} \beta^{\tau-a} w_0}_{\text{outside option}} \right\},$$

$$(6)$$

for $a \in \{1, 2, 3\}$. In the final year of a player's career the continuation value is zero:

$$V_4^{t+1}(q_3, \vec{z}_t) = 0.$$

The vector of aggregate state variables is $\vec{z}_{t-1} = (m_{1,t-1}, m_{2,t-1}, \widehat{q}_{2,t-1})$. m_{1t} and m_{2t} denote the masses of young and middle-aged players who choose to play in period t. $\widehat{q}_{2t}$ denotes the threshold quality for participation of middle-aged players, so that a middle-aged player in period t plays if, and only if, q_{i1} is above $\widehat{q}_{2t}$. Last period's quality threshold for middle-aged players appears as a state variable because it affects the quality of old players in period t. A similar threshold exists for old players, but it does not enter as a state variable because the players who were old last period are no longer playing tennis. An individual player's quality appears as a state variable for middle-age and old players. It does not appear for young players because young players all start the period with the same quality q_0.

The participation thresholds $\widehat{q}_{2t}$ and $\widehat{q}_{3t}$ are defined by the requirement that a player at the threshold is indifferent between playing or not:

$$[\widehat{q}_{2t}]: \qquad \mathbb{E}\left[q_2 \cdot p(Q_t) + \beta V_3^{t+1}(q_2, \vec{z}_t) \mid q_1 = \widehat{q}_{2t}, \vec{z}_{t-1}\right] = (1+\beta) w_0, \qquad (7)$$

$$[\widehat{q}_{3t}]: \qquad \mathbb{E}\left[q_3 \cdot p(Q_t) \mid q_2 = \widehat{q}_{3t}, \vec{z}_{t-1}\right] \qquad\qquad = w_0. \qquad (8)$$

Since young players are identical when they decide whether to play or not, the mass of players who enters, m_{1t}, is determined by the requirement that all young players are indifferent between playing or not:

$$[m_{1t}]: \qquad \mathbb{E}\left[q_1 \cdot p(Q_t) + \beta V_2^{t+1}(q_1, \vec{z}_t) \mid \vec{z}_{t-1}\right] \qquad = (1+\beta+\beta^2) w_0. \quad (9)$$

We assume that there is always an interior solution for m_{1t}.

The masses of middle-aged and old players that choose to play tennis in period t, are given by

$$m_{2t} = m_{1,t-1} \cdot \mathbb{P}[q_1 \geq \widehat{q}_{2t}], \text{ and}$$
$$m_{3t} = m_{1,t-2} \cdot \mathbb{P}[q_1 \geq \widehat{q}_{2,t-1} \wedge q_2 \geq \widehat{q}_{3t}].$$

Putting these expressions together, the total quality of all players, Q_t, is given by

$$Q_t = m_{1t} \mathbb{E}[q_1] + m_{2t} \mathbb{E}[q_2 \mid q_1 \geq \widehat{q}_{2t}] + m_{3t} \mathbb{E}[q_3 \mid q_1 \geq \widehat{q}_{2,t-1} \wedge q_2 \geq \widehat{q}_{3t}].$$

A.5 Three useful lemmas

We now present three lemmas that will be useful later. All three are fairly intuitive, and their proofs are found in section B of the appendix.

Lemma 2. V_a^t *is increasing in player quality for all* $a \in \{1,2,3\}$. *That is,*

$$q' > q \Rightarrow V_a^t\left(q', \vec{z}_{t-1}\right) \geq V_a^t\left(q, \vec{z}_{t-1}\right).$$

Moreover, these inequalities are strict if the player chooses to play in period t rather than take the outside option.

Lemma 3. *There exists a unique value for* $\widehat{q}_{2t}$ *(and* $\widehat{q}_{3t}$*) such that middle-aged (old) players in period t choose to play when* $q > \widehat{q}_{2t}$ *(*$q > \widehat{q}_{3t}$*), while those with quality* $q < \widehat{q}_{2t}$ *(*$q < \widehat{q}_{3t}$*) choose to exit and take the outside option.*

Lemma 4. *Suppose the market is in a steady state. Then* $\widehat{q}_{3t} \geq \widehat{q}_{2t} \geq \widehat{q}_{1t}$. *That is, as players age their exit cutoffs also (weakly) rise.*

The intuition for Lemma 4 is that younger players are willing to play with a lower quality in the current period, even if expected earnings are below w_0, because they anticipate enjoying a higher quality, and thus higher earnings, in the future. In contrast, old players have no future period so they will only be willing to play if their expected earnings are above w_0.

Appendix B Proofs

B.1 Proof of Lemma 1

Proof. When a player switches to the new racquet his quality grows according to

$$
\begin{aligned}
\Delta \log q'_{ia} &= \log q'_{ia} - \log q_{i,a-1} \\
&= \log A' - \log A + \lambda' \log x_{ia} - \lambda \log x_{i,a-1} \\
&\quad + (1-\lambda') \log y_{ia} - (1-\lambda) \log y_{i,a-1} \\
&= \alpha_a + \varepsilon_{ia} + \log A' - \log A + (\lambda' - \lambda)(\log x_{i,a-1} - \log y_{i,a-1}) \quad\text{(B.1)}
\end{aligned}
$$

where q'_{ia} is player i's quality using the new racquet. Defining

$$
u_{ia} = \log A' - \log A + (\lambda' - \lambda)(\log x_{i,a-1} - \log y_{i,a-1}), \quad\text{(B.2)}
$$

(B.1) becomes

$$
\Delta \log q'_{ia} = \alpha_a + \varepsilon_{ia} + u_{ia} = \Delta \log q_{ia} + u_{ia} \quad\text{(B.3)}
$$

∎

B.2 Proof of Lemma 2

Proof. We prove this by induction, and so begin with V_3^t. First, note that $\mathbb{E}[q_3 \cdot p(Q_t) \mid q_2, \vec{z}_{t-1}]$ is strictly increasing in q_2, while the wage of the outside option w_0 is unrelated to q_2. Thus, V_3^t is weakly increasing in q_2 and strictly increasing if the player chooses to play in period t.

Now we turn to V_a^t and assume V_{a+1}^{t+1} is increasing in player quality. First, note that $\mathbb{E}\left[q_a \cdot p(Q_t) + \beta V_{a+1}^{t+1}(q_a, \vec{z}_t) \mid q_{a-1}, \vec{z}_{t-1}\right]$ is weakly increasing in q_{a-1}. This is true because $\mathbb{E}[q_t \cdot p(Q_t) \mid q_{a-1}, \vec{z}_{t-1}]$ is strictly increasing in q_{a-1} while $\mathbb{E}\left[\beta V_{a+1}^{t+1}(q_a, \vec{z}_t) \mid q_{a-1}, \vec{z}_{t-1}\right]$ is weakly increasing in q_{a-1}. As before, the present value of the outside option, $\sum_{\tau=0}^{3-a} \beta^\tau w_0$, is unrelated to q_{a-1}. Thus, V_a^t is weakly increasing in q_a and strictly increasing if the player chooses to play in period t. ∎

B.3 Proof of Lemma 3

Proof. An old player ($a = 3$) entering period t with quality q_2 will continue playing if, and only if, the value of playing is no less than the outside option:

$$\mathbb{E}\left[q_3 \cdot p(Q_t) \mid q_2, \vec{z}_{t-1}\right] \geq w_0. \tag{B.4}$$

Note that

$$\lim_{q_2 \to 0} \mathbb{E}\left[q_3 \cdot p(Q_t) \mid q_2, \vec{z}_{t-1}\right] = 0$$

$$\lim_{q_2 \to \infty} \mathbb{E}\left[q_3 \cdot p(Q_t) \mid q_2, \vec{z}_{t-1}\right] = \infty.$$

Also, note that the left-hand side of (B.4) is a strictly increasing, continuous function of q_2. Thus, as long as w_0 is positive and finite, equation (B.4) will hold with equality at exactly one point. Therefore, $\widehat{q}_{3t}$ exists and is unique.

A middle-aged player entering period t with quality q_1 will continue playing if, and only if, the value of playing for one more period is no less than the present value of the outside option:

$$\mathbb{E}\left[q_2 \cdot p(Q_t) + \beta V_3^{t+1}\left(q_2, \vec{z}_t\right) \mid q_1, \vec{z}_{t-1}\right] \geq (1 + \beta)w_0. \tag{B.5}$$

The first term of the left-hand side of (B.5) is strictly increasing in q_1, while from Lemma 2 we know that the second term is weakly increasing in q_1. Thus, the entire term is strictly increasing in q_1. It also likewise follows that it is continuous. Following the same reasoning as the previous paragraph, it must be that $\widehat{q}_{2t}$ exists and is unique. ∎

B.4 Proof of Lemma 4

Proof. We first show $\widehat{q}_{3t} \geq \widehat{q}_{2t}$. Since we are in a steady state, we drop the dependence on t. By way of contradiction, suppose that $\widehat{q}_2 > \widehat{q}_3$. Consider a quality level

48

$q^* \in (\widehat{q}_3, \widehat{q}_2)$. Then it must be the case that

$$\mathbb{E}\left[q_2 \cdot p(Q) + \beta V_3(q_2, \vec{z}) \mid q_1 = q^*, \vec{z}\right] < (1 + \beta) w_0 \tag{B.6}$$

$$\mathbb{E}\left[q_3 \cdot p(Q) \mid q_2 = q^*, \vec{z}\right] > w_0 \tag{B.7}$$

From (B.6) we can write

$$(1 + \beta) w_0 > \mathbb{E}\left[q_2 \cdot p(Q) \mid q_1 = q^*, \vec{z}\right] + \beta \mathbb{E}\left[V_3(q_2, \vec{z}) \mid q_1 = q^*, \vec{z}\right]$$
$$\geq \mathbb{E}\left[q_2 \cdot p(Q) \mid q_1 = q^*, \vec{z}\right] + \beta w_0$$

Combining this with (B.7) we get

$$\mathbb{E}\left[q_2 \cdot p(Q) \mid q_1 = q^*, \vec{z}\right] < w_0 < \mathbb{E}\left[q_3 \cdot p(Q) \mid q_2 = q^*, \vec{z}\right]$$

But this is a contradiction because the distribution of $q_2 \mid q_1 = q^*$ first-order stochastically dominates the distribution of $q_3 \mid q_2 = q^*$, which means it must be the case that

$$\mathbb{E}\left[q_2 \cdot p(Q) \mid q_1 = q^*, \vec{z}\right] > \mathbb{E}\left[q_3 \cdot p(Q) \mid q_2 = q^*, \vec{z}\right].$$

which is a contradiction. It is straightforward to extend this proof to show $\widehat{q}_{2t} \geq \widehat{q}_{1t}$. ∎

B.5   Proof of Proposition 1

Proof. As players improve, they invest more in the skill that the racquet they are using puts more weight on. From (3) and (4) we know

$$\log x_{ia} - \log y_{ia} = \log x_{i,a-1} - \log y_{i,a-1} + \frac{2\lambda - 1}{\lambda^2 + (1 - \lambda)^2}(\alpha_a + \varepsilon_{ia}). \tag{B.8}$$

By iterating equation (B.8), we find

$$\log x_{ia} - \log y_{ia} = \log x_0 - \log y_0 + \frac{2\lambda - 1}{\lambda^2 + (1 - \lambda)^2}\sum_{\tau=1}^{a}(\alpha_\tau + \varepsilon_{i\tau}). \tag{B.9}$$

49

Similarly, iterating equation (5) gives

$$\log q_{ia} = \log q_0 + \sum_{\tau=1}^{a} (\alpha_\tau + \varepsilon_{i\tau})$$

$$\Rightarrow \sum_{\tau=1}^{a} (\alpha_\tau + \varepsilon_{i\tau}) = \log q_{ia} - \log q_0. \tag{B.10}$$

Substituting (B.10) into (B.9) yields

$$\log x_{ia} - \log y_{ia} = \log x_0 - \log y_0 + \frac{2\lambda - 1}{\lambda^2 + (1-\lambda)^2} (\log q_{ia} - \log q_0). \tag{B.11}$$

Substituting (B.11) into (B.2) gives us

$$u_{ia} = \log A' - \log A + (\lambda' - \lambda) (\log x_0 - \log y_0)$$
$$+ (\lambda' - \lambda) \frac{2\lambda - 1}{\lambda^2 + (1-\lambda)^2} (\log q_{i,a-1} - \log q_0). \tag{B.12}$$

This implies

$$u_{ia_i(t)} - u_{ja_j(t)} = (\lambda' - \lambda) \frac{2\lambda - 1}{\lambda^2 + (1-\lambda)^2} \left(\log q_{i,a_i(t-1)} - \log q_{j,a_j(t-1)} \right). \tag{B.13}$$

Since $\lambda' < \lambda$ and $\lambda > 0.5$, (B.13) implies that $u_{ia_i(t)} < u_{ja_j(t)}$. ∎

B.6   Proof of Corollary 1

Proof. First note that equation (5) implies

$$\log q_{ia_i(t)} - \log q_{ja_j(t)} = \log q_{i,a_i(t-1)} - \log q_{j,a_j(t-1)} + \alpha_{a_i(t)} - \alpha_{a_j(t)} + \varepsilon_{ia_i(t)} - \varepsilon_{ja_j(t)}$$

$$\tag{B.14}$$

and equations (B.3) and (B.12) imply

$$
\begin{aligned}
\log q'_{ia_i(t)} - \log q'_{ja_j(t)} &= \log q_{ia_i(t)} - \log q_{ja_j(t)} + u_{ia_i(t)} - u_{ja_j(t)} \\
&= \underbrace{\frac{\lambda\lambda' + (1-\lambda)(1-\lambda')}{\lambda^2 + (1-\lambda)^2}}_{B} \left(\log q_{i,a_i(t-1)} - \log q_{j,a_j(t-1)} \right) \\
&\quad + \alpha_{a_i(t)} - \alpha_{a_j(t)} + \varepsilon_{ia_i(t)} - \varepsilon_{ja_j(t)}.
\end{aligned} \tag{B.15}
$$

Since $\lambda > .5$ and $\lambda' < \lambda$, it must be the case that $0 \le B < 1$. Equation (B.14) implies

$$
\begin{aligned}
&\mathbb{P}\left[\log q_{ia_i(t)} > \log q_{ja_j(t)} \right] \\
&= \mathbb{P}\left[\varepsilon_{ia_i(t)} - \varepsilon_{ja_j(t)} > -\left(\log q_{i,a_i(t-1)} - \log q_{j,a_j(t-1)} + \alpha_{a_i(t)} - \alpha_{a_j(t)} \right) \right], \quad \text{(B.16)}
\end{aligned}
$$

while equation (B.15) implies

$$
\begin{aligned}
&\mathbb{P}\left[\log q'_{ia_i(t)} > \log q'_{ja_j(t)} \right] \\
&= \mathbb{P}\left[\varepsilon_{ia_i(t)} - \varepsilon_{ja_j(t)} > -\left(B\left(\log q_{i,a_i(t-1)} - \log q_{j,a_j(t-1)} \right) + \alpha_{a_i(t)} - \alpha_{a_j(t)} \right) \right]. \\
&\tag{B.17}
\end{aligned}
$$

Equations (B.16), (B.17), and $B < 1$ together imply

$$
\begin{aligned}
\mathbb{P}\left(q'_{ia_i(t)} > q'_{ja_j(t)} \mid q_{i,a_i(t-1)} > q_{j,a_j(t-1)} \right) & \\
&< \mathbb{P}\left(q_{ia_i(t)} > q_{ja_j(t)} \mid q_{i,a_i(t-1)} > q_{j,a_j(t-1)} \right). \quad \text{(B.18)}
\end{aligned}
$$

Since Kendall's τ has the property that $E(\tau) = \mathbb{P}(x_{it} > x_{jt} \mid x_{i,t-1} > x_{j,t-1}) - \mathbb{P}(x_{it} < x_{jt} \mid x_{i,t-1} > x_{j,t-1})$, equation (B.18) implies that the introduction of the new racquet reduces the rank correlation of period-to-period player quality in the period when the racquet is introduced. ∎

B.7 Proof of Proposition 2

Proof. Given that we are in a steady state, we know from Lemma 4 that the distribution of quality for older players has a higher truncation point than the distribution for younger players. Moreover, the quality of older players is shifted right, relative to that of younger players, by α_2 and/or α_3. For both reasons, the median quality of older players in period t is greater than the median quality of younger players in period t. This implies that $\mathbb{P}\left[q_{ia_i(t)} > q_{ja_j(t)} \mid a_i(t) > a_j(t)\right] > .5$. By Proposition 1, this implies $\mathbb{P}\left[u_{ia_i(t)} < u_{ja_j(t)} \mid a_i(t) > a_j(t)\right] > .5$. ∎

B.8 Proof of Proposition 3

Proof. We show the effect of the technological shock on the exit rates of the oldest players is ambiguous by considering the two examples described in the text. First, we show it is possible for the exit rate for the oldest players to decrease. If the demand for tennis output is perfectly elastic, $p'(Q) = 0$, then the price per unit of quality is unchanged by the new technology, and so, by (8), $\widehat{q}'_{3t} = \widehat{q}_{3t}$. By assumption, the new racquet is enough better that all players switch in the same period, so that $q'_{i,2} > q_{i,2} \forall i$. Thus there exists an $\varepsilon > 0$ such that all players i for whom $q_{i,2} \in (\widehat{q}_{3t} - \varepsilon, \widehat{q}_{3t})$, and so were going to exit, now choose to continue playing since $q'_{i,2} \geq \widehat{q}'_{3t}$. Thus, it is possible for the exit rate for the oldest players to decrease.

Next, we show it is possible for the exit rate for the oldest players to increase. Consider another extreme case where demand is not perfectly elastic, but $\lambda = 1$ and $\lambda' = 0$. The technological shock completely devalues all investments any of the oldest players have made and their quality is now equal to that of the youngest players: $q_{i,2} = q_0$.

However, by (6), $V_2^{t+1}(q_1, \vec{z}_t) \geq (1 + \beta)w_0$ for all possible q_1 and $\vec{z}_t$, with the inequality strict for some q_1 and $\vec{z}_t$. Thus, as long as the probability that a new player continues to play in the second period is greater than zero, then

$$\mathbb{E}\left[V_2^{t+1}(q_1, \vec{z}_t) \mid q_0, \vec{z}_{t-1}\right] > (1 + \beta)w_0.$$

Therefore, (9) implies a new player's expected earnings are less than w_0:

$$\mathbb{E}\left[q_1 \cdot p(Q_t) \mid q_0, \vec{z}_{t-1}\right] < w_0. \tag{B.19}$$

By (5), if an old and young player start the period at the same quality, the young player's expected quality at the end of the period is greater than the old player's expected quality at the end of the period:

$$\mathbb{E}\left[q_1 \mid q_0 = q_0, \vec{z}_{t-1}\right] > \mathbb{E}\left[q_3 \mid q_2 = q_0, \vec{z}_{t-1}\right].$$

Therefore, the old player's expected earnings in the current period are less than the young player's expected earnings, which is in turn less than w_0 by (B.19):

$$w_0 > \mathbb{E}\left[q_1 \cdot p(Q_t) \mid q_0, \vec{z}_{t-1}\right] > \mathbb{E}\left[q_3 \cdot p(Q_t) \mid q_2 = q_0, \vec{z}_{t-1}\right].$$

Therefore, by (8), $\widehat{q}_{3t} > q_0$ and all old players exit. ∎

Appendix C Discussion of heterogeneous initial skills

In general, allowing for heterogeneous initial skills complicates the analysis without adding additional insight. However, an alternative model we could consider is one where players are born with heterogeneous skills, and, while players could improve both skills, they could not change their initial mix of skills. In this model a change in racquet technology would change the type of players who enter. This alternative model leads to an important additional interpretation of our results: that technological change can hurt some workers who are born without the skills needed to succeed.

This alternative model has many of the same predictions as our model, however it leads to a very different prediction regarding player entry and exit. The alternative model predicts that young players who entered before the racquet change will exit at higher rates when the new racquet is introduced. The intuition for this is that while older players see their quality fall, given their lifetime of investment, many of them can still profitably play while the new players, whose endowment of skill better

match the racquet, develop their skills. On the other hand, many young players who entered before the racquet change were playing at a loss, relative to their outside option, to develop the skills to earn profits later in their careers. With the racquet change, they no longer have the endowment of skills needed to have a viable path toward earning profits, and so will exit.

Put differently, in the alternative model, the new racquet leads to a much larger decrease in the continuation value for existing players. And this decrease in continuation values is more pronounced for younger players. At its extreme, this would lead to nearly all players in the second year of their professional career exiting.

As Figure 15 shows, we find that exit rates for the young are basically unchanged, while exit rates for the old climb significantly. This suggests that the alternative model does not match the data from professional tennis.

Appendix D Additional tables

Table D.1: Player-year summary statistics (not in SCC)

	Mean	Median	Std. dev.
Age	22.5	21.6	5.10
Annual singles wins	0.23	0	0.56
Annual singles matches	1.80	1	1.43
Observations	16313		

Notes: These summary statistics are only calculated for player-years not in the strongly connected component, but include all of their wins and matches, regardless of whether their opponent was in the strongly connected component.

Table D.2: Number of player-years excluded from the SCC

Annual wins	Annual losses				
	0	1	2	3+	Total
0	0	9,729	2,279	1,362	13,370
1	186	1,043	482	622	2,333
2	61	125	103	180	469
3+	28	37	14	62	141
Total	275	10,934	2,878	2,226	16,313

Notes: This table calculates the number of player-years in each cell that are excluded from the strongly connected component.

Table D.3: Elasticity of cohort prize money with respect to cohort R16 Grand Slam appearances

	(1)	(2)
log(Appearances)	1.212***	1.214***
	(0.0428)	(0.0370)
Observations	68	68
R^2	0.924	0.969
Year FE	No	Yes

Standard errors in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Notes: The table reports results from regressing a birth cohort's (log) prize money in year t on its R16 Grand Slam appearances in year t. The sample is restricted to five-year birth cohorts between 1970–1989 and years 1990–2015.

Figure D.1: Total prize money over time

Notes: The figure plots the total prize money at Wimbledon and Roland-Garros between 1970–1993. Prize money was converted to U.S. dollars and corrected for inflation. The dashed lines mark the years when professional tennis players were transitioning to composite racquets.

Appendix E Results limited to Grand Slams

In this section we limit our data to the four Grand Slam tournaments. Because the Australian Open has changed the size of its initial round over time, we further limit ourselves to the round of 64 and later rounds. This has the benefit of giving us a consistent set of tournaments over our entire sample and allows us to address the possibility that our results are being driven by changes in the number of tournaments. Limiting ourselves to the Grand Slams also has a cost, as it reduces our sample and makes it impractical to estimate player quality.[34] Instead, we proxy for player quality using the number of Grand Slam matches in which a player competes.[35] We find that we can reproduce our results on this more limited data set. In some cases, the magnitude of the changes are smaller than in our main analysis (Figures E.5, E.6, E.8), while in others the changes are larger (Figures E.2 and E.3).

---

[34]We can only estimate player quality for between 15 and 50 percent of the players in any given year.

[35]An alternative measure of player quality is the number of matches they win. Given the tournament structure of tennis, this is highly correlated with the number of matches they compete in, with a correlation coefficient of 0.97.

Several figures in our main analysis already limited the sample to Grand Slams, and we do not reproduce these results. This includes Figures 8, 9, and 19. We also do not reproduce results involving prize money, including Figures 13 and 14.

E.1 Evidence for skill-altering technical change

Figure E.2 is very similar to Figure 6, and shows that the returns to height increased when the composite racquets were introduced. This is evidence that the composite racquets were a skill-altering technical change.

Figure E.2: Relationship between number of matches played and height over time

Notes: The figure plots the regression coefficient from regressing a player's number of matches played in Grand Slam tournaments on his height (in inches) in each year (circles) and a four-year lagged moving average (solid line). The dashed lines mark the years when professional tennis players were transitioning to composite racquets. The figure reports the p-value of a t-test of whether the return to height before 1978 differed from the return between 1985–1999.

E.2 Year-to-year rank correlation of player quality fell temporarily

Again, Figure E.3 is largely the same as Figure 7, and shows a drop in the year-to-year rank correlation of player quality, as proxied by the player's number of Grand Slam matches.

Figure E.3: Year-to-year rank correlation of number of matches played

Notes: This figure plots a measure of rank correlation (Kendall's τ) between a player's number of Grand Slam matches in consecutive years (circles). If a player did not appear in year t but did in year $t-1$ or $t+1$, we imputed zero matches in year t. The solid line plots a four-year lagged moving average. The vertical dashed lines mark the years of the racquet transition (1978–1984). The reported p-value corresponds to an F-test for whether the pre-1978, 1978–1984, and 1985–1999 periods have the same slopes and intercepts.

E.3 Younger players gained relative to older players

Figure E.4 is very similar to Figure 10, and shows that the transition to the composite racquets increased the share of matches played by young players and decreased the share of matches played by older players.
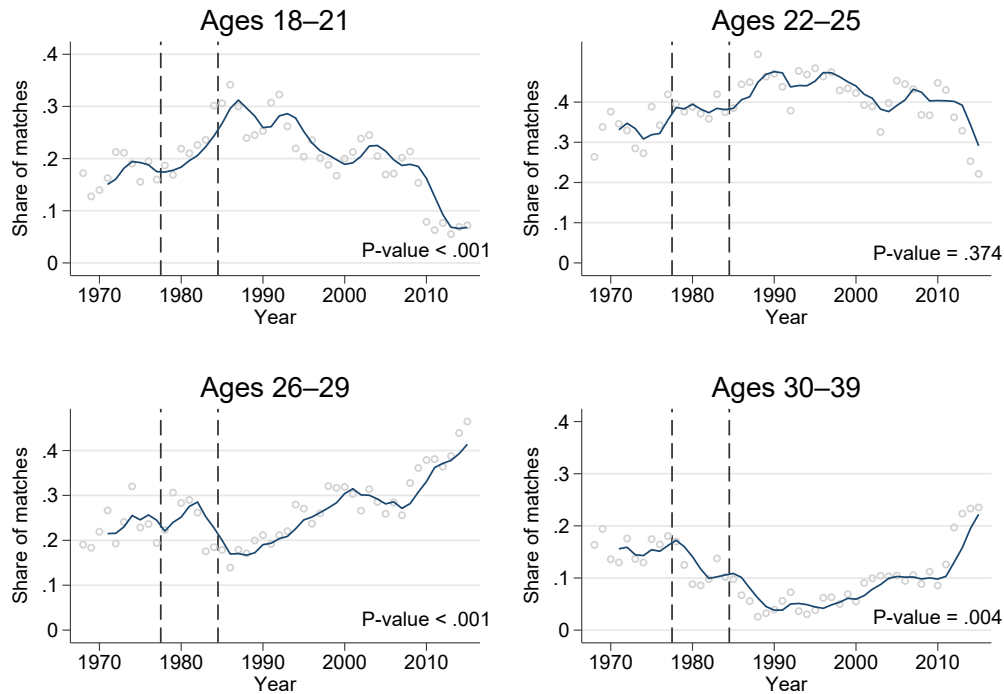

Figure E.4: Share of Grand Slam matches by age group over time

Notes: The figure plots the share of Grand Slam matches by age group for each year (circles) and a four-year lagged moving average (solid line). The vertical dashed lines mark the years of the racquet transition (1978–1984). The reported p-value corresponds to an F-test for whether the pre-1978, 1978–1984, and 1985–1999 periods have the same slopes and intercepts.

In Figure E.5 we plot the median age of players separately for those who are above or below the median number of Grand Slam matches for that year. While Figure E.5 shows a similar pattern as Figure 11, the age gap between the median above- and below average player is significantly smaller we cannot reject the null hypothesis that the trendlines are parallel between 1970–1999. This may be due to

59

the fact that, by limiting ourselves to Grand Slams, we are already restricted to the best players on tour. Thus, we don't find a stark difference between the best players and the *very* best players.
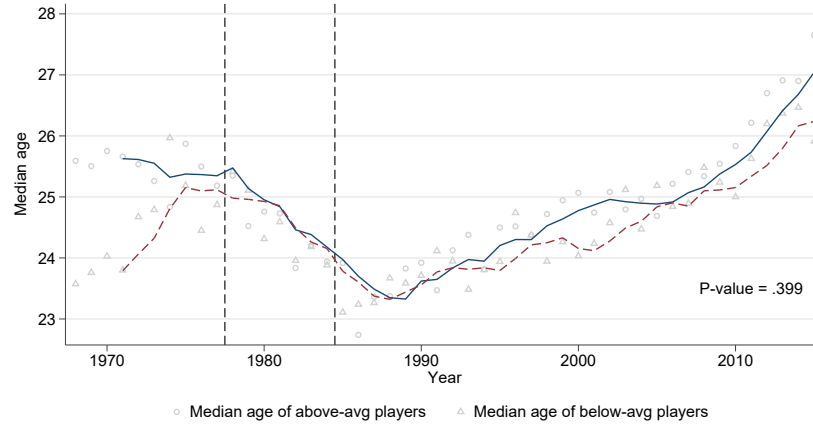

Figure E.5: Median age of above- and below-average players over time

Notes: The figure plots the median age of above- and below-average players in each year (circles and triangles) and a four-year lagged moving average (solid and dashed lines). Above- and below-average are defined using the median number of Grand Slam matches played in the given year. The vertical dashed lines mark the years of the racquet transition (1978–1984). The reported p-value corresponds to an F-test for whether above-average and below-average players have parallel trends between 1970–1999.

Figure E.6 shows, as does Figure 12, that the benefit of age is at its lowest in the mid 1980s. However, the difference between the pre-transition and post-transition gradient is less pronounced than in Figure 12.

E.4 Exit rates of older players rose relative to younger players

Figure E.7 shows the same patterns as Figure 15, showing that the exit rates for older players increased during the transition. Note that an "exit" in Figure E.7 means failing to qualify for a Grand Slam in year $t + 1$ whereas in Figure 15, in the main text, an "exit" meant failing to be included in the strongly connected component in year $t + 1$.

Figure E.6: Relationship between number of Grand Slam matches and age over time

Notes: The figure plots the age-matches gradient in each year (circles) and a four-year lagged moving average (solid line). The vertical dashed lines mark the years of the racquet transition (1978–1984). The reported p-value corresponds to an F-test for whether the pre-1978, 1978–1984, and 1985–1999 periods have the same slopes and intercepts.

While Figure E.8 has a local minimum between 10 and 15 years, the right side of the figure does not show the dramatic rise that Figure 16 does and we cannot reject the hypothesis of a single linear line fitting the data. These results are a little quirky and difficult to interpret. While the average age a player first competed in a Grand Slam is typically a year later than the average age a player first entered the tour for those who were 10 or younger in 1980, for those who were 21 or older in 1980, the average age a player first competed in a Grand Slam is *lower* than the average age a player first was on the tour. The seeming contradiction, that players are competing in Grand Slams before they are on the tour, comes from the sample selection rules. The data in the main text uses all players in the SCC while this section limits the data to those players who ever competed in a round of 64 in a Grand Slam.

Figure E.9 shows, as does Figure 17, that the age distribution shifted younger during the transition to composite racquets.
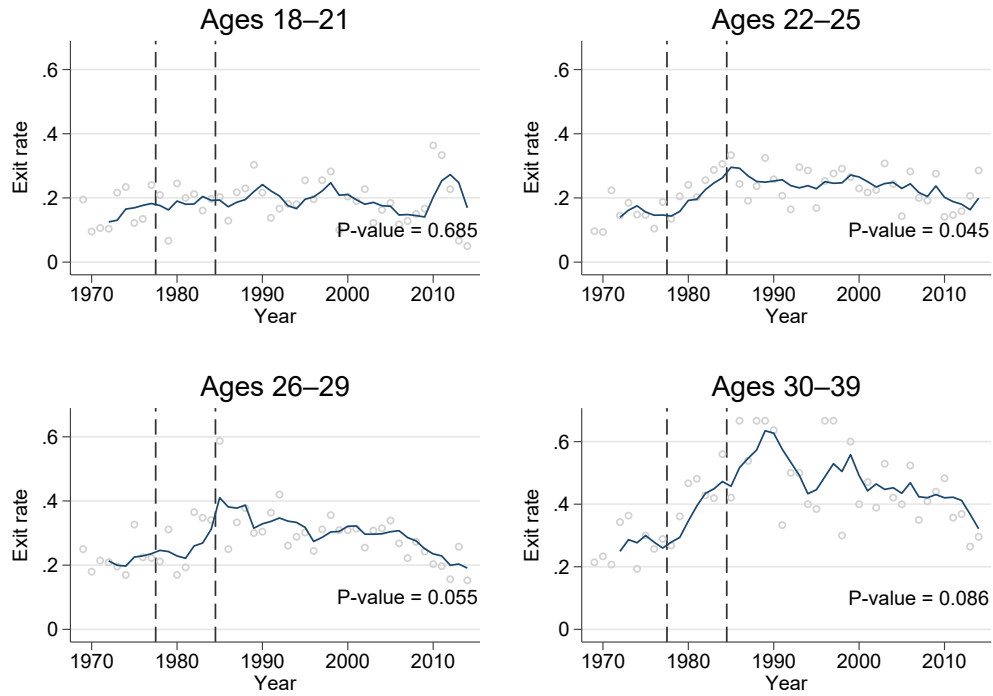
Figure E.7: Exit rates by age group over time

Notes: The figure plots the exit rate by age group for each year (circles) and a four-year lagged moving average (solid line). A player "exits" in year *t* if he plays at least one Grand Slam match in year *t* but does not play any Grand Slam matches in year *t* + 1. The vertical dashed lines mark the years of the racquet transition (1978–1984). The reported p-value corresponds to an F-test for whether the pre-1978, 1978–1984, and 1985–1999 periods have the same slopes and intercepts.
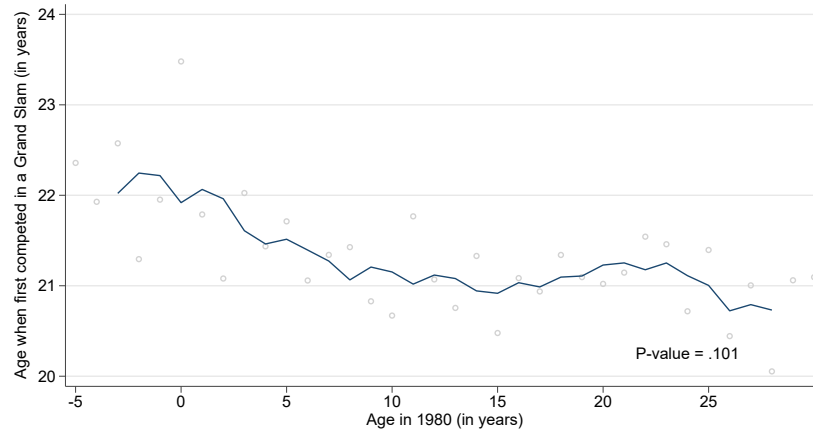
Figure E.8: Age when first competed in Grand Slam by age in 1980

Notes: The figure plots the mean age when a player first competed in a Grand Slam for each birth year, reported as age in 1980 (circles) and a five-year centered moving average (solid line). The vertical dashed lines mark the years of the racquet transition (1978–1984). The reported p-value corresponds to an F-test for whether the trend for points to the left of 10 have a different intercept and slope than the trend for points to the right of 10.
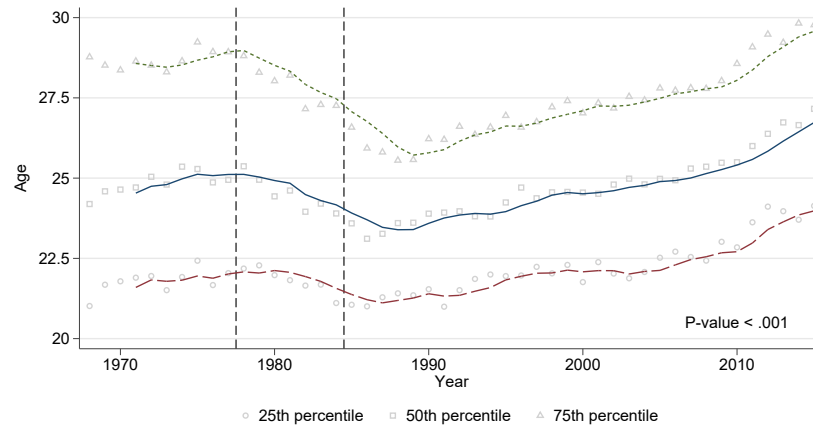

Figure E.9: Age distribution over time

Notes: The figure plots the quartiles of the age distribution of players competing in the Grand Slams in each year, along with four-year lagged moving averages. The vertical dashed lines mark the years of the racquet transition (1978–1984). The reported p-value corresponds to an F-test for whether the pre-1978, 1978–1984, and 1985–1999 periods have the same slopes and intercepts for the median age.

E.5 Cross-sectional inequality during the transition

Figure E.10 is comparable to Figure 18, and shows a small dip in cross-sectional inequality during the transition.
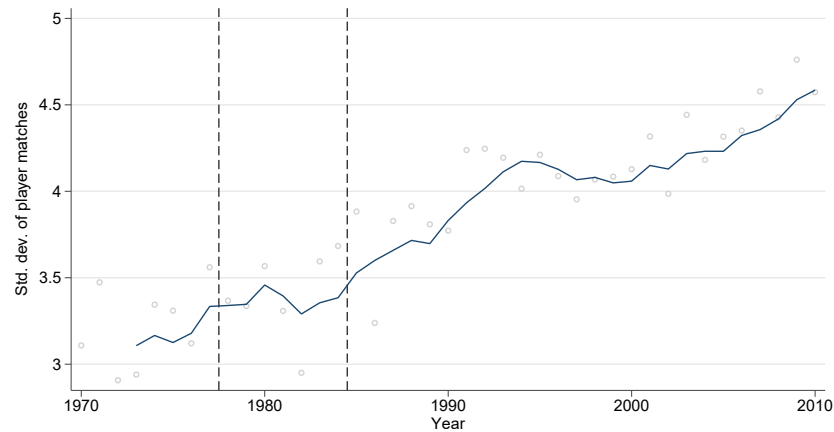

Figure E.10: Cross-sectional standard deviation of player Grand Slam matches

Notes: The figure plots the standard deviation of players' Grand Slam matches in each year, along with four-year lagged moving averages. The vertical dashed lines mark the years of the racquet transition (1978–1984)