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Peak athletic performance and ageing: Evidence from baseball

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Abstract
Baseball players exhibit a pattern of improvement and decline in performance; however, differing lengths of careers and changes in rules and characteristics of the game complicate assessments of age-related effects on performance. This study attempts to isolate the impact of age on several player skills while controlling for relevant outside factors using longitudinal data from 86 seasons of Major League Baseball. The results indicate that players age in different skills in accord with studies of ageing in other athletic contests. For overall performance, multiple-regression estimates indicate that hitters and pitchers peak around the age of 29 – later than previous estimates. Athletic skills such as hitting and running peak earlier than skills that rely heavily on experience and knowledge, such as issuing and drawing walks.

Keywords: *Ageing, peak performance, baseball*

Introduction

Baseball offers a unique opportunity to study human ageing and peak athletic performance. The availability of performance records over a century, stability of rules, independent nature of performances, and many athletic skills employed provide an excellent natural laboratory. These characteristics allow researchers to hold constant many exogenous factors while observing performances of many athletes throughout their careers. Furthermore, baseball involves strategic interaction, where opposing players compete against each other in a series of individual contests; therefore, strategic thinking and game-theory play vital roles in influencing performance. This means that even as physical skills diminish, there is room for players to compensate by improving non-physical skills through experience.

Evidence from literature on physiology of exercise indicates that peak physiological function for men occurs just before age 30 years and then regresses between 0.75% and 1.0% per year; however, studies of ageing in athletics have found that the impact of age differs according to the athletic skills used in the sport. Activities involving strength, speed, and endurance favour younger athletes, while activities that require high skill and less vigorous physical stress have later peaks (Gabbard, 2004).

Schulz and Curnow (1988) identified the most common age at which athletes experience peak performance in several sports using performance records from the twentieth century. The authors found that despite athletes' improvement in overall performance over time, the age at which they set records remained stable. This indicates that natural ageing plays a major role in determining when athletes reach maximum performance. In sports that rely heavily on strength and explosive performance (e.g. swimming, sprinting, and tennis), athletes peak in their early to mid-twenties, while sports that require more endurance, skill, and knowledge (e.g. long-distance running and golf) yield peaks closer to 30. For baseball players, who use skills that range from purely athletic (sprinting from base to base) to strategic knowledge (predicting and identifying pitches), authors have found that the mean age for peak performances to be between 27 and 28 years.

Over and Thomas (1995) surveyed a sample of old and young golfers to examine the impacts of age in a sport where athletic demands are modest. While golfers tended to lose driving distance with age, they responded to the loss of this skill through more conservative playing strategies and stronger mental fortitude that limited negative emotional responses. Using a sample of professional golfers, Baker and colleagues (Baker, Deakin, Horton, & Pearce, 2007) found support for the compensation of deteriorating

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athletic skill with improvement in other areas of the game.

Some researchers have studied ageing in baseball directly. Using a sample of 66 batters from 1955 to 1960, Krohn (1983) estimated 28 to be the peak age for batting average. Schulz and colleagues (Schulz, Musa, Staszewski, & Siegler, 1994) used a longitudinal data set of baseball players active from the 1950s through the 1970s to examine ageing. Peaks for these players tended to occur at the age of 27, with a few skills peaking earlier (stealing bases) and some later (walks). Albert (2002) estimated ageing trajectories of baseball hitters using a Bayesian exchangeable model to modify regression estimates of individual players according to career paths of those born in the same decade. Using adjusted linear weights per-plate appearance to proxy player performance, the author found that peak ages rose over the course of the twentieth century: players born in the 1910s peaked at age 28, while those born in the 1960s peaked at age 29.8. Fair (2007) examined several measures of performance for hitters and pitchers over the course of their careers. For hitters, peak on-base-plus-slugging occurred between 27 and 28, and peak on-base percentage occurred between 28 and 29. For pitchers, a player's peak earned run average occurred between 24 and 27. Also, some studies originating from the ''sabermetrics'' community – an informal group of baseball fans who study baseball – found peak age to be age 27 (James, 1982; Silver, 2006).

In summary, the evidence indicates that athletes peak in their mid- to late twenties, depending on the skills used by the athletes. If one considers sports to be arranged along a continuum of athleticism from the least to the most athletic, baseball is on the former end; thus, baseball players are likely to peak later than athletes in other sports where strength and speed are greater determinants of relative performance.

This study examines the ageing pattern of several skills important to Major League Baseball players during the twentieth and twenty-first centuries, while accounting for rules-related differences in which players work – an issue that previous studies did not address. The results indicate that both hitters and pitchers peak around age 29. This is older than some estimates of peak performance, but it is in line with the general understanding of human physiological function. Consistent with studies of ageing in specific athletic skills, baseball players peak earlier (later) in abilities that require more (less) physical stress. Players in the present peak later than their predecessors did earlier in the twentieth century; however, because the change does not follow a constant pattern of improvement over time, it is not obvious why this is the case.

Methods

Data and sample issues

Data come from the Lahman Baseball Database, 5.4, which is an open access database. The sample includes 86 seasons from 1921 to 2006 for players who made their debuts after 1920. The year 1921 is generally considered to be the beginning of the modern era of baseball, as run-scoring increased in response to the prohibition of ball-scuffing and the rise of the home run (Palmer & Gillette, 2005).

The study of ageing in baseball is challenging, because individuals have different skill sets and different reasons for performance changes over time. And to complicate this is the fact that determinants of when players begin and end their careers are not random. Good players begin and end their careers earlier and later than mediocre players, because improving and declining good players contribute more to winning than improving and declining marginal players.

To minimize the selection bias, this study limits the sample of players from ages 24 to 35, even though many players' careers extend beyond this age range. In addition, players must have careers of at least 10 years and must accrue a minimum of 5000 plate appearances for hitters or 4000 batters-faced for pitchers. For this paper, plate appearances are defined as the sum of at-bats, walks, and hit-by-pitches. The traditional definition of plate appearances includes sacrifice flies, but they are excluded from this study because they were not recorded until 1953. Albert and Bennett (2001) demonstrated that this minor adjustment does little harm to estimating run production. The batter–pitcher confrontation minima are lower for pitchers to include some relief pitchers. Most models include per-season batter–pitcher confrontation minima of 300 for hitters and 200 for pitchers – approximately one standard deviation below the league mean for the samples – to ensure a sample size large enough to reflect true performance.

Another potential problem with using baseball performance measures to study ageing is that, despite the homogeneity of the game over time, individual metrics can be biased by team-mate contributions. However, Bradbury and Drinen (2008) demonstrated that team-mates have almost no effect on the individual batting performances of one another; therefore, it is appropriate to assume that individual performance metrics are not biased by team-mate interactions.

Empirical procedure

Equation (1) is estimated with Stata 9 statistical software using a multiple-regression analysis

technique designed for longitudinal data. The specific technique employed is the Baltagi and Wu (1999) random-effects method, which corrects for detected first-order serial-correlation. Estimates using player fixed-effects yield nonsensical results. In many specifications the model estimates peak age to be in the teens and early-twenties – far younger than the peak age estimates from other, more physically demanding sports and less than the mean age that players enter the league. Further investigation revealed this to be the result of interaction between the fixed-effects and the correction for serial-correlation. When the correction for serial-correlation is excluded, the fixed-effects results are similar to the random-effects estimates reported in this paper.

$$Z_{it} = \beta_1 \mathrm{Age}_{it} + \beta_2 \mathrm{Age}_{it}^2 + \beta_3 \overline{Z}_i + \Theta D_{it} + v_i + \varepsilon_{it} \quad (1)$$

where Z_{it} is the z-score of the performance of player i at age t, relative to the mean of the league in the year of observation.

Several measures of performance are used to capture the changes in skills in different areas. For hitters, adjusted linear weights, on-base-plus-slugging, on-base percentage, batting average, slugging average, walks per-plate appearance, doubles-plus-triples per-at-bat, and home runs per-at-bat are examined independently. Several popular baseball metrics (e.g. runs, runs-batted-in, wins, and saves) are not included because they are influenced heavily by team-mate contributions. Table I contains a list of the abbreviations used in the tables and figures, together with an approximation of the degree of athleticism for each performance area.

Adjusted linear weights is derived from a measure developed by Thorn and Palmer (1984), which assigns weights to baseball events based on their contributions to run production. The traditional formula is: linear weights = (0.46 × singles) + (0.8 × doubles) + (1.02 × triples) + (1.4 × home runs) + [0.33 × (walks + hit-by-pitches)] + (0.3 × stolen bases) − (0.6 × caught stealing) − [0.25 × (at-bats − hits)]. The modified formula used for this study does not include stolen base events because caught stealing was not recorded for both leagues until 1950. Linear weights is useful for two reasons. First, it correlates with run scoring more than any other performance metrics. Second, it measures overall performance, because it is not normalized for attempts like the other performance metrics. An older player could be capable of performing at a higher standard with infrequent play, which would be masked by the normalized measures.

Table I. Abbreviations and degree of athleticism.

Abbreviation	Full name	Degree of athleticism
Hitters		
AVG	Batting average	Moderate
BB	Walks per-plate appearance	Low
DPT	Double plus triples per-at-bat	High
HR	Home runs per-at-bat	Moderate
LWTS	Adjusted linear weights	Moderate
OBP	On-base percentage	Low
OPS	On-base-plus-slugging	Moderate
SLG	Slugging average	Moderate
Pitchers		
BB9	Walks allowed per-nine innings	Moderate
ERA	Earned-run average	Moderate
HR9	Home runs allowed per-nine innings	Moderate
K9	Strikeouts per-nine innings	High
RA	Runs-allowed average	Moderate

The batting average, the sum of hits divided by at-bats, measures the rate at which a batter reaches base via a hit. The slugging average is a batting average that weights each base hit according to the base reached by the hitter (i.e. a single is counted once, a double is counted twice, etc.). The on-base percentage is the sum of hits, walks, and hit-by-pitches divided by plate appearances. The on-base-plus slugging – the sum of on-base percentage and slugging average, and also developed by Thorn and Palmer (1984) – correlates strongly adjusted linear weights and explains nearly as much of the variance of runs scored across teams, yet is simpler to calculate. Hitting relies more on athletic skill than reaching base via a walk, because a player can draw a walk without even swinging the bat. If baseball players compensate for a loss of athleticism, then walking is an obvious area to improve. Walks per-plate appearance, doubles plus triples per-at-bat, and home runs per-at-bat are hitting-skill components of the overall metrics. Individual investigation of these metrics ought to identify impacts of age that are missed with metrics of aggregate production.

For pitchers, earned-run average, runs-allowed average, strikeouts per-nine innings, walks allowed per-nine innings, and home runs allowed per-nine innings measure performance. All the metrics are denominated per nine innings pitched, in accord with baseball convention. Earned runs and runs both proxy a pitcher's overall ability to prevent runs; the former making an additional adjustment for obvious defensive mistakes. Bradbury (2007) demonstrated some weaknesses of earned-run average and runs-allowed average as proxies of pitcher skill; however, the deficiencies are minor for this type of analysis. The three areas that pitchers control without the aid of team-mates are strikeouts, walks, and home runs. Analysing these components avoids some problems with earned-run average and runs-allowed average and allows for the assessment of these important pitching skills.

A potential problem with using longitudinal data to analyse changes in player performance over time is that while baseball rules have remained somewhat stable since the early twentieth century, the relative nature of competition and differences in environments in which players play complicate the analysis. The playing field conditions are not uniform across teams, because park dimensions, altitudes, and weather can aid or hinder players who play in these environments. The limits on who can play baseball also affect the competition that players face when they generate statistics often used to evaluate ageing. Racial segregation, immigration, war, competition for athletes in other sports, and expansion are all factors that affect the performances of players. Gould (1996) developed a theory for how the composition of league talent influences individual performances, and Schmidt and Berri (2003) found support for this theory in baseball. Changing rules (e.g. the height of a legal pitching mound and the definition of the strike zone), improved equipment (e.g. bats, balls, and gloves), and the popularity of performance-enhancing drugs (e.g. anabolic steroids and amphetamines) can influence the play of one era relative to other eras. Furthermore, players switching teams throughout their careers complicates identifying changes in performance over time.

To account for differences in run production across home ballparks, park factors adjust for playing field bias for adjusted linear weights, earned-run average, and runs-allowed average, which are denominated in terms of runs. Park factors for hitters and pitchers are listed in the Lahman Baseball Database, 5.4. To control for differences across eras, in each player season, a player's performance is compared with the league mean using a z-score (Z). Each player is compared to the mean performance of the league, relative to the standard deviation of the performance statistic across the league in the year of observation. This is especially important for players whose careers overlap large changes in competition, where changes due to external factors could be confused with ageing.

Age is a continuous variable measured as the number of days since birth to 1 July of the season of analysis – the approximate midpoint – divided by 365.25. A quadratic function offers the hypothesized inverted-U shape of performance, but does not necessarily generate the best fit. Specifications including polynomials of higher orders did not improve the fit of the regression estimates or yield statistically significant coefficients beyond the squared term. Furthermore, the simplicity of maximizing quadratic functions eases the task of identifying peak age (peak age $= \beta_1/(2\beta_2)$).

To quantify the impact of ageing, it is necessary to control for the quality of the player in the skill analysed. Thus, the mean z-score performance of the player in that statistic over his career is included. Also, changes in the performance of the league in each year reflect information about the relative performance of the player. Although the dependent variable is normalized to measure relative performance, including dummy indicator variables for each league season, vector $\mathbf{D}$ adds an additional control for any missed information resulting from playing conditions. v is a player-specific error term and ε is a standard error term. Table II lists summary statistics for all variables.

Table II. Summary statistics.

Variable	Observations	Mean	s	Min.	Max.
Hitters					
LWTS	4627	1.65082	1.88391	−3.64104	9.08504
OPS	4627	0.24894	0.38116	−2.41147	2.51692
OBP	4627	0.19669	0.31377	−2.39276	1.68750
SLG	4627	0.26545	0.45337	−2.07260	3.22268
AVG	4627	0.17729	0.28543	−2.28968	1.74463
BB	4627	0.37089	0.56707	−1.49685	2.76174
DPT	4627	0.09664	0.38996	−0.81329	10.74676
HR	4627	0.76493	1.03000	−1.00459	6.29089
Age	4627	29.92824	3.33059	24.00274	35.99453
Age^2	4627	906.79010	199.97800	576.13140	1295.60600
Pitchers					
ERA	4145	−0.0668186	0.2531527	−0.9690756	1.699667
RA	4145	−0.0677439	0.2560017	−1.027703	1.544651
K9	4145	0.0816049	0.682946	−1.813823	3.178801
BB9	4145	−0.0970035	0.3636897	−1.631747	1.805833
HR9	4145	−0.03724	0.3270565	−1.353524	2.260573
Age	4145	30.2553	3.301526	24.00548	35.99726
Age^2	4145	926.2805	199.3952	576.2629	1295.803

Note: Hitting and pitching variables expressed as z-scores.
Source: The Lahman Baseball Database, 5.4.

There is the possibility that players age differently according to ability. To examine if the ageing function of superstar players differs from that of ordinary players in the sample, equation (1) is also estimated using a sample of players who have been admitted to the National Baseball Hall of Fame.

This study also examines the overall performance of hitters (linear weights) and pitchers (earned-run average) in smaller groups designated by decade of birth, similar to Albert (2002). It is reasonable to anticipate that players in the present will peak later than past players because of advances in health and wealth. Slicing the sample into decades of birth uses the between-effects of players from the same birth cohort – who ought to age at similar rates – to estimate the effects of age, rather than using the entire 86-year sample. In addition, the sample of hitters does not restrict players by a minimum number of plate appearances per season. Older players might need more rest to produce at anticipated standards and also could be more likely to miss time because of injury. Thus, older players could appear to age less than they do as they play less and, in some cases, could be dropped from the sample with a plate-appearance minimum.

Results

Hitters

Figure 1 displays the frequency with which hitters experience their peak season by age in adjusted linear weights. The modal peak age is 28, with 14% of all hitters having their best season at this age. Fifty-two percent of players experience their best season from age 27 to 31. Although age 28 – a player between his 28th and 29th birthdays – is the most frequent peak age, the next most frequent ages are 31, 30, and 29. The mean and median ages for peak performance are both approximately 29.5, a full year higher than the mode.

Table III reports the regression estimates of equation (1), which quantify the impact of age, controlling for relevant characteristics for the entire sample. For all hitting metrics, the age coefficients are of the anticipated sign and are statistically significant. Peak age ranges from 28.35 for batting average to 32.30 for walks per-plate appearance. Figure 2 maps the ageing functions of individual skills, with a vertical dashed line at the age of 30 to give a benchmark for comparison.

The last row of Table III lists the peak age estimates for Hall of Fame hitters. The peak age estimates for this exceptional sample lie both above and below the estimates from the full sample and, except for doubles plus triples per-at-bat, are similar.

Table IV reports the regression estimates on linear weights by decade of birth and does not restrict the sample by yearly plate appearance minima. For the full sample, the peak-age estimate is similar to the estimate in Table III. By decade of birth, the earliest peak age (28.05) occurs for players born from 1901 to 1910 and the latest peak age (30.53) occurs for players born in the 1960s – a 2½-year spread between the oldest and most recent birth-decade groups. The estimated coefficients of age are statistically significant for all sub-samples except for those players born in the 1910s.

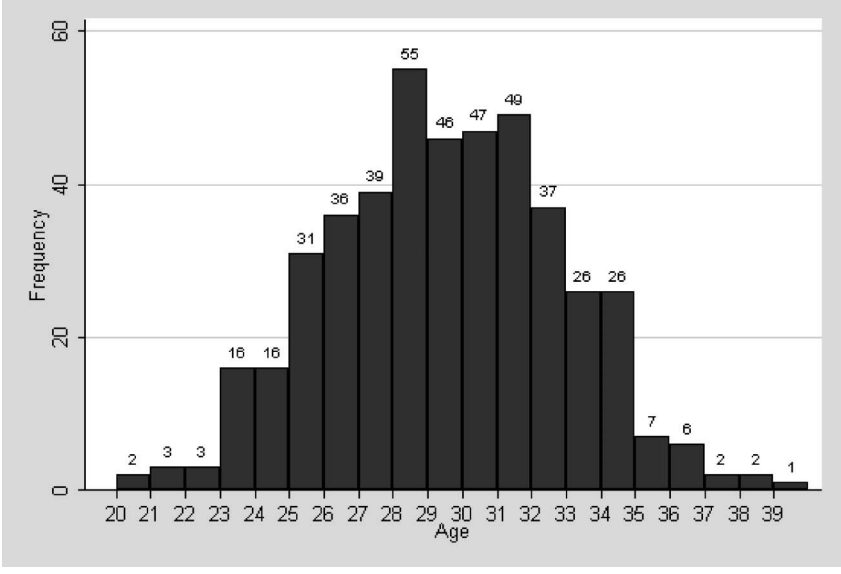

Figure 1. Age at which players achieve peak performance in adjusted linear weights.

Table III. The impact of age on hitting performance (1921–2006).

	LWTS	OPS	OBP	SLG	AVG	BB	DPT	HR
Age	1.3221827	0.220792	0.1840429	0.2265646	0.1217102	0.2279219	0.0618912	0.4183447
	[10.74]**	[8.41]**	[8.25]**	[7.58]**	[5.39]**	[7.11]**	[13.28]**	[7.61]**
Age^2	−0.0224774	−0.0037893	−0.0030628	−0.0039638	−0.0021463	−0.0035283	−0.0010952	−0.0069987
	[10.95]**	[8.66]**	[8.24]**	[7.95]**	[5.70]**	[6.60]**	[2.00]**	[7.64]**
Mean career performance	1.204972	0.9825663	0.9229312	1.0110073	0.8477	1.013081	0.4089168	1.095775
	[61.03]**	[55.38]**	[51.43]**	[60.04]**	[38.22]**	[73.68]**	[2.12]**	[81.34]**
Observations	4627	4627	4627	4627	4627	4627	4627	4627
Players	450	450	450	450	450	450	450	450
Overall R^2	0.60	0.54	0.51	0.58	0.38	0.69	0.24	0.73
Peak age (entire sample)	29.41	29.13	30.04	28.58	28.35	32.30	28.26	29.89
Peak age (Hall of Fame†)	28.51	28.52	29.80	27.81	27.92	32.44	32.72	28.54

Note: Absolute value of *z*-statistics in brackets. *Significant at $P < 0.05$. **Significant at $P < 0.01$. †Includes 75 players and 836 observations. Constants and league-season dummy coefficients not reported.

Pitchers

Figure 3 displays the frequency with which pitchers in the sample peak in earned-run average by age. As they are with hitters, the mean and median ages exceed the mode. The most common age for a player to peak in earned-run average is 28, with the mean and median ages of peak performances being 30.38 and 30.09 respectively.

Table V reports the estimates of equation (1) for pitchers and Figure 4 maps the ageing functions of individual skills, with a vertical dashed line at the age of 30. For all of the pitching metrics, the age coefficients are statistically significant. Peak age ranges from 23.56 for strikeouts per-nine innings to 32.46 for walks allowed per-nine innings.

For the Hall of Fame sample, the coefficient estimates of the age variables are not statistically significant for any of the skills; nevertheless, the peak-age estimates are similar to the full sample estimates. Although the estimated ageing function for strikeouts has no peak, the continuous decline mirrors the fact that strikeouts peak early in pitchers' careers.

Table VI reports the impact of age on earned-run average by birth decade. Peak age ranges from 27.61 in the 1900s to 31.61 in the 1920s. However, the coefficient estimates are statistically significant for the 1930s, 1950s, and 1960s only.

Discussion

In attempts to isolate peak performance age, it is tempting to identify the most frequent age at which players experience their peak performances. However, the difference between mean and mode peak ages both for hitters and pitchers highlights the potential problem of using the mode to estimate peak performance. A possible reason for this is that athletes are vulnerable to stochastic injury shocks unrelated to physical ageing, which reduce performance. In baseball, such injuries occur from collisions, being hit by a pitch, falls, and so on that have little to do with ageing. However, the longer a player plays, the more likely it is that he will experience one of these injuries. Thus, players have fewer opportunities to experience peak seasons on the latter side of their careers, because players are more likely to suffer a stochastic injury shock the longer they play. This theory explains why mean and mode peak performance ages can deviate from one another in the manner observed.

The regression estimates indicate that hitters age similarly across the different performance measures, but the peaks vary according to skills. For adjusted linear weights, which is not normalized for playing time, players peak at 29.41 years. This is similar to

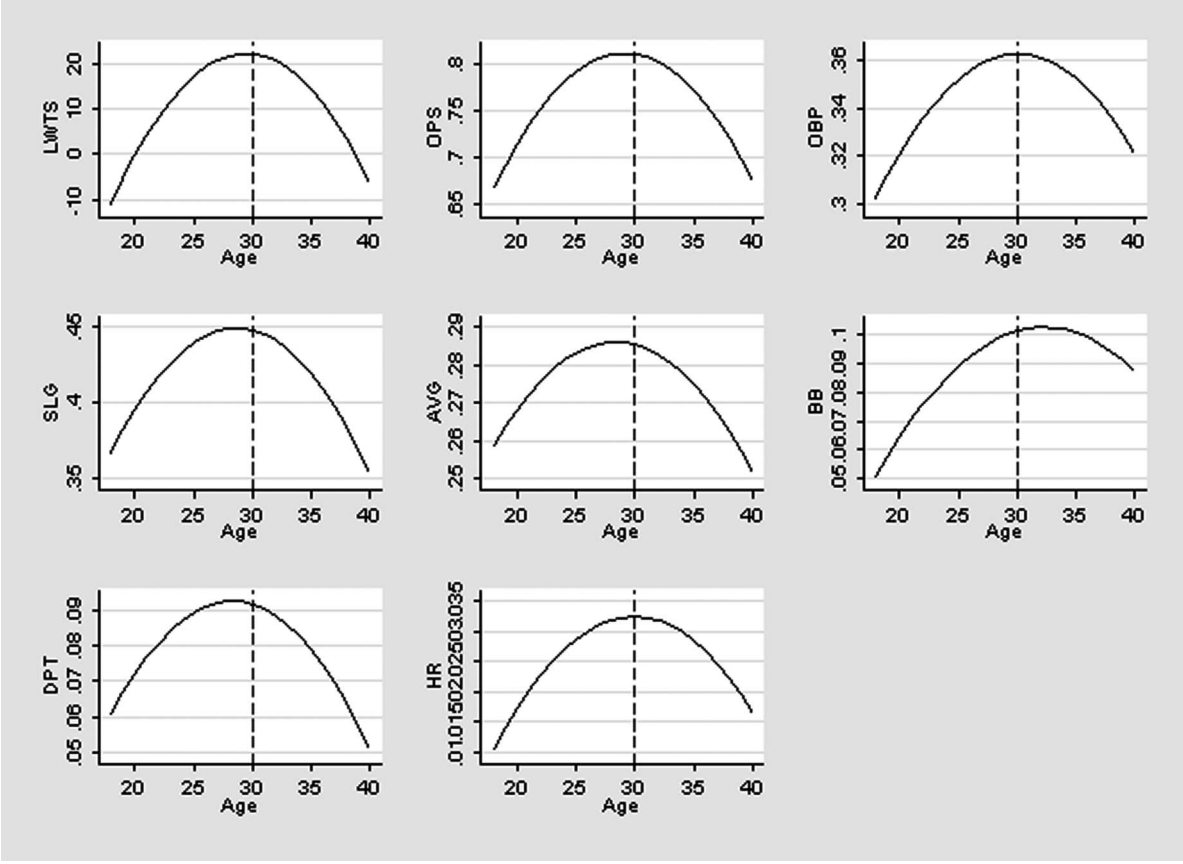

Figure 2. Impact of age on hitting skills (based on sample mean at peak age).

the peak-age estimate of 29.13 for on-base plus-slugging, which is normalized for playing time.

In terms of specific hitting skills, player ageing functions differ considerably. The on-base percentage captures the raw ability to reach base and peaks at 30.04. The two main components of on-base percentage – hitting and walking – peak 4 years apart as batting average and walks per-plate appearance peak at 28.35 and 32.38 respectively. As players age, they improve at coaxing walks from pitchers. This could be a product of experience – improved knowledge of the strike zone and strategic anticipation of pitch selection – or a response to a loss in hitting ability that forces players to learn how to walk so as to compensate for waning hitting skill. This finding is consistent with studies of ageing in other athletic events, which find that skills requiring less physical ability peak later than those requiring greater physical ability.

The slugging average peaks at 28.58, similar to the peak age of batting average, which is not surprising given that slugging average is a weighted batting average. Breaking slugging average into its components, doubles plus triples per-at-bat peaks at 28.26 and the rate at which players hit home runs peaks at 30.08. This suggests that slugging average declines because players lose foot speed rather than hitting power, which results in hits that were previously doubles and triples becoming singles. The fact that home runs per-at-bat peaks later than doubles plus triples per-at-bat indicates that hand–eye coordination and strategic thinking that contribute to hitting power are not the main factors in the early peak of slugging average.

Pitchers, in terms of overall run prevention, peak at 29.16 and 29.05 in earned-run average and runs-allowed average – similar to the peak of age of adjusted linear weights for hitters. However, pitchers show a wider variation in ageing across skills than batters do.

Strikeouts peak at 23.56, which is about the mean age at which pitchers begin their Major League careers. Effective strikeout pitchers typically rely on pitch speed, which requires strength in muscles and tendons. It is not surprising that this is the first skill to deteriorate. It also may explain the popularity of ulnar collateral ligament reconstruction – or ''Tommy John'' – surgery, which replaces a ligament in the elbow that is stretched from consistent hard throwing. A strikeout pitcher whose ball-speed is

Table IV. The impact of age on adjusted linear weights by decade of birth.

	Full sample	1900s	1910s	1920s	1930s	1940s	1950s	1960s
Age	1.5128549	1.1599263	0.6890367	1.8969652	1.8142365	2.0302369	1.3123527	1.0516856
	[13.32]**	[3.50]**	[1.08]	[4.97]**	[4.84]**	[7.48]**	[4.26]**	[3.67]**
Age^2	−0.0256485	−0.0206759	−0.0118097	−0.0322076	−0.0318873	−0.0344295	−0.0229493	−0.0172266
	[13.58]**	[3.75]**	[1.12]	[5.10]**	[5.12]**	[7.62]**	[4.48]**	[3.62]**
Mean career performance	1.1643856	1.2374777	1.0637101	1.2255288	1.1902751	1.1910301	1.2412219	1.1051863
	[61.32]**	[23.51]**	[10.57]**	[16.51]**	[25.77]**	[28.14]**	[23.91]**	[27.60]**
Observations	5242	518	341	495	578	1025	896	1182
Players	450	45	34	43	49	86	75	100
Overall R^2	0.57	0.71	0.50	0.56	0.68	0.57	0.53	0.57
Peak age	29.49	28.05	29.17	29.45	28.45	29.48	28.59	30.53

Note: Absolute value of z-statistics in brackets. *Significant at $P < 0.05$. **Significant at $P < 0.01$. Constants and league-season dummy coefficients not reported.

falling might need the replacement to continue pitching in the majors as he is already in the decline phase of this skill when his career begins.

A pitcher's ability to prevent walks peaks at 32.47, nearly 9 years later than peak strikeout age, which helps explain how pitchers can improve in overall run prevention while diminishing in strikeout ability. Also, the improvement in walk prevention with age is more dramatic than the decline in strikeout ability. From the peak age for strikeouts to the peak age for walks – ages 24 to 32 – the strikeout rate declines by 6%. In contrast, walks are 24% lower at age 24 than they are at 32.

Notably, both pitchers and hitters peak in their ability to prevent and earn walks in their early thirties. This indicates that walking ability improves because of knowledge. It is possible for batters to walk more because they refrain from swinging at marginal pitches when their bat-speed declines. Unlike batters, pitchers must exert physical effort with every pitch; thus, it is likely a mental understanding of how to work the strike zone that causes walks per-plate appearance to peak later both for hitters and pitchers.

Exceptional players who have been elected to the Hall of Fame age similarly to other players. Compared with the full sample of hitters, the Hall of Fame players peak slightly earlier in terms of overall production. For skills, batting average, slugging average, and home runs per-at-bat peak marginally earlier, and on-base percentage and walks per-plate appearance peak at about the same age as for ordinary players. Doubles plus triples per-at-bat peaks 4½ years later for Hall-of-Famers, which indicates that elite hitters continue to improve and maintain some speed and dexterity while other players are in decline. For pitchers, peak age estimates for the Hall-of-Fame and full samples are similar, although the coefficient estimates are not statistically significant. The lack of such significance for pitchers and the slightly different ageing functions of individual skills for hitters and pitchers are likely to be the product of the greatly reduced sample size. The Hall-of-Fame-hitters sample includes 75 players and 836 observations compared with 450 players and 4627 observations in the full sample. For pitchers, the Hall-of-Fame sample includes 26 players and 289 observations compared with the 436 players and 4145 observations in the full sample.

In terms of changes in peak age over time, neither hitters nor pitchers showed a consistent pattern of improvement from the beginning of the twentieth century to the present. The variation could be a product of random fluctuations in the data or individual factors within these player cohorts rather than reflections of a delay in ageing. This is consistent with Schulz and Curnow (1988), who

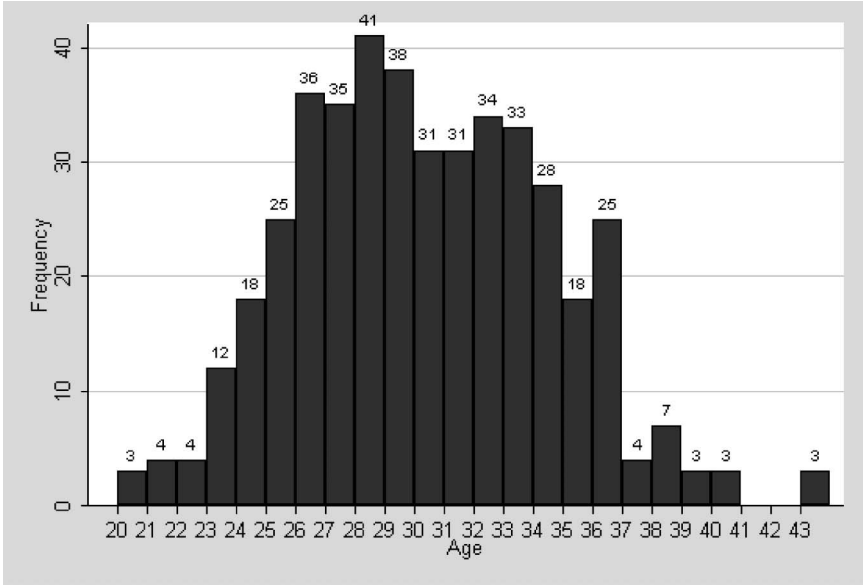

Figure 3. Age at which players achieve peak performance in earned-run average.

Table V. The impact of age on pitching performance (1921–2006).

	ERA	RA	Strikeouts	Walks	Home Runs
Age	−0.1284451	−0.1331105	0.1094797	−0.2023614	−0.1000888
	[5.07]**	[5.21]**	[2.09]*	[6.44]**	[3.15]**
Age^2	0.0022021	0.0022913	−0.0023231	0.0031162	0.0018272
	[5.24]**	[5.41]**	[2.67]**	[5.99]**	[3.47]**
Mean career performance	0.4094038	0.4354495	1.0115532	0.7786164	0.6024456
	[13.34]**	[14.18]**	[44.00]**	[34.82]**	[20.08]**
Observations	4145	4145	4145	4145	4145
Players	436	436	436	436	436
Overall R^2	0.11	0.12	0.54	0.39	0.17
Peak age (entire sample)	29.16	29.05	23.56	32.47	27.39
Peak age (Hall of Fame†)	29.08	28.89	–	33.45	25.94

Note: Absolute value of z-statistics in brackets. *Significant at $P < 0.05$. **Significant at $P < 0.01$. †Includes 26 players and 289 observations, and age coefficients are not statistically significant. Constants and league-season dummy coefficients not reported.

found that the age at which athletes set performance records has not improved with time.

The regression results can be used to map the ageing function over a playing career. Table VII reports the rates of improvement and decline for several player skills, relative to the hypothetical peak of a typical player in the sample. For ages less than 24 and greater than 35 years, the estimated effects are generated from out-of-sample predictions based on the in-sample estimated ageing function. The bold numbers highlight performances within 10% of the mean player peak according to the regression estimates reported in Tables III and V. For hitters, linear weights has the tightest peak range (27–32, six years), which is not surprising because it is the only measure that includes the quantity and quality of play. For on-base-plus-slugging, players perform within 10% of the peak for 17 years. As for hitting skills, improvement and decline is stable for batting average (21 years within 10% of the peak) and steep for home runs per-at-bat (9 years within 10% of the peak).

For pitchers, the rise and decline for overall performance is moderate, with earned-run average and runs-allowed average having 12 and 13 seasons within 10% of the peak. These measures are not adjusted for playing time, thus they could underestimate the impact of pitcher ageing. Although pitcher strikeout ability peaks early, relative to other skills, the decline is stable as pitchers do not fall below 10% of their peak ability in this area until age 35.

It would appear that baseball players are able to maintain a higher standard of play in the midst

Table VI. The impact of age on earned-run average by decade of birth.

	1900s	1910s	1920s	1930s	1940s	1950s	1960s
Age	−0.0779768	−0.0489224	−0.0015678	−0.2837691	0.0234108	−0.2125403	−0.1338937
	[0.84]	[0.53]	[0.02]	[2.87]**	[0.32]	[3.15]**	[2.16]*
Age^2	0.001412	0.0008521	0.0000248	0.004846	−0.0003873	0.0037399	0.002284
	[0.93]	[0.56]	[0.02]	[2.95]**	[0.32]	[3.34]**	[2.22]*
Mean career performance	0.6680511	0.1745902	0.1984397	0.2234573	0.4743816	0.5296866	0.6555978
	[5.27]**	[1.88]	[3.38]**	[2.01]*	[5.99]**	[6.52]**	[9.56]**
Observations	465	325	405	460	642	803	836
Players	53	40	45	47	61	81	85
Overall R^2	0.16	0.15	0.15	0.11	0.15	0.17	0.21
Peak age	27.61	28.71	31.61	29.28	30.22	28.42	29.31

Note: Absolute value of z-statistics in brackets. *Significant at $P < 0.05$. **Significant at $P < 0.01$. Constants and league-season dummy coefficients not reported.

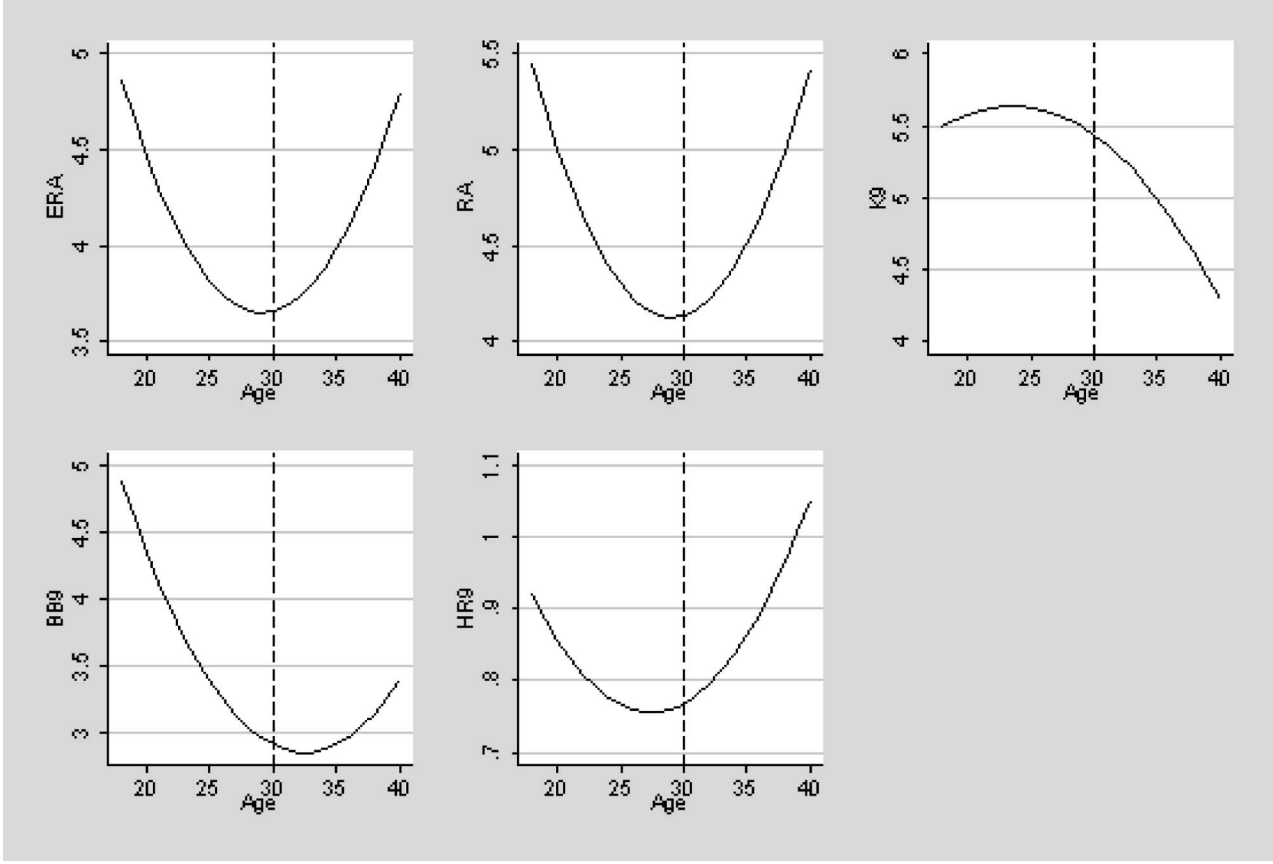

Figure 4. Impact of age on pitching skills (based on sample mean at peak age).

of decline in some skill areas by improvement in others. This is consistent with studies of golf that have found players compensating for diminishing physical skills by improving areas that are less affected by age. As hitters lose foot-speed on the basepaths, their ability to reach base via walks continues to improve. Pitchers experience their highest strikeout rates early in their careers, but improve at keeping hitters off the bases by allowing fewer walks. In both cases, improved knowledge of the game and opposing players, as well as a stronger mental fortitude, could contribute to continued success as physical skills deteriorate.

Table VII. Percent difference from peak performance by age.

	Hitting								Pitching				
Age	LWTS	OPS	OBP	SLG	AVG	BB	DPT	HR	ERA	RA	K9	BB9	HR9
18	−149.71%	−17.62%	−16.66%	−18.28%	−9.55%	−50.72%	−34.15%	−67.63%	−33.23%	−31.98%	**−2.71%**	−70.66%	−21.63%
19	−124.59%	−14.60%	−14.01%	−14.98%	**−7.80%**	−43.87%	−27.81%	−56.73%	−27.55%	−26.45%	**−1.81%**	−61.22%	−17.26%
20	−101.77%	−11.86%	−11.59%	−12.01%	**−6.22%**	−37.52%	−22.12%	−46.79%	−22.39%	−21.45%	**−1.10%**	−52.46%	−13.38%
21	−81.25%	**−9.40%**	−9.39%	−9.37%	**−4.81%**	−31.66%	−17.08%	−37.80%	−17.77%	−16.97%	**−0.56%**	−44.37%	**−10.00%**
22	−63.04%	**−7.23%**	**−7.43%**	**−7.05%**	−3.59%	−26.30%	−12.69%	−29.77%	−13.68%	−13.01%	**−0.20%**	−36.96%	**−7.10%**
23	−47.12%	−5.35%	**−5.70%**	−5.06%	−2.55%	−21.44%	**−8.95%**	−22.70%	−10.13%	−9.58%	**−0.01%**	−30.22%	**−4.70%**
24	−33.51%	**−3.75%**	**−4.20%**	−3.40%	**−1.68%**	−17.07%	**−5.86%**	−16.58%	**−7.11%**	−6.68%	**0.00%**	−24.16%	**−2.79%**
25	−22.21%	**−2.43%**	**−2.92%**	**−2.07%**	−0.99%	−13.20%	**−3.42%**	−11.43%	**−4.62%**	**−4.29%**	**−0.16%**	−18.77%	**−1.37%**
26	−13.20%	**−1.39%**	**−1.88%**	**−1.06%**	**−0.48%**	−9.83%	**−1.63%**	**−7.23%**	−2.66%	−2.43%	**−0.51%**	−14.07%	**−0.44%**
27	**−6.50%**	**−0.64%**	**−1.06%**	−0.38%	**−0.15%**	−6.95%	**−0.49%**	−3.98%	**−1.24%**	**−1.10%**	**−1.02%**	−10.03%	**0.00%**
28	**−2.10%**	**−0.18%**	**−0.48%**	−0.03%	**0.00%**	**−4.56%**	**0.00%**	**−1.70%**	−0.35%	**−0.29%**	**−1.71%**	**−6.67%**	**−0.05%**
29	**0.00%**	**0.00%**	**−0.13%**	**0.00%**	−0.03%	**−2.68%**	**−0.16%**	**−0.37%**	**0.00%**	**0.00%**	**−2.58%**	−3.99%	**−0.60%**
30	**−0.20%**	**−0.10%**	**0.00%**	−0.30%	−0.23%	**−1.29%**	**−0.97%**	**0.00%**	**−0.18%**	**−0.24%**	−3.63%	**−1.99%**	**−1.64%**
31	**−2.71%**	**−0.49%**	**−0.10%**	−0.93%	**−0.61%**	**−0.40%**	**−2.43%**	−0.59%	**−0.89%**	**−1.00%**	**−4.85%**	**−0.65%**	**−3.17%**
32	**−7.52%**	**−1.17%**	**−0.44%**	**−1.89%**	**−1.18%**	**0.00%**	−4.53%	**−2.13%**	**−2.14%**	**−2.28%**	**−6.24%**	**0.00%**	**−5.19%**
33	−14.63%	**−2.12%**	**−1.00%**	**−3.17%**	**−1.92%**	**−0.10%**	**−7.29%**	−4.63%	−3.92%	**−4.09%**	**−7.82%**	**−0.02%**	**−7.70%**
34	−24.04%	−3.37%	**−1.80%**	**−4.78%**	−2.83%	**−0.70%**	−10.70%	**−8.09%**	−6.23%	−6.43%	−9.56%	**−0.72%**	−10.71%
35	−35.76%	**−4.89%**	**−2.82%**	**−6.72%**	−3.93%	**−1.79%**	−14.75%	−12.51%	**−9.08%**	−9.29%	−11.49%	**−2.09%**	−14.21%
36	−49.78%	**−6.70%**	**−4.07%**	−8.98%	**−5.21%**	−3.38%	−19.46%	−17.88%	−12.45%	−12.67%	−13.59%	**−4.14%**	−18.19%
37	−66.10%	**−8.80%**	−5.55%	−11.57%	−6.66%	**−5.46%**	−24.82%	−24.21%	−16.37%	−16.58%	−15.86%	**−6.86%**	−22.67%
38	−84.72%	−11.18%	**−7.27%**	−14.49%	**−8.29%**	**−8.04%**	−30.82%	−31.50%	−20.81%	−21.01%	−18.31%	−10.26%	−27.64%
39	−105.64%	−13.84%	**−9.21%**	−17.74%	−10.10%	−11.12%	−37.48%	−39.74%	−25.79%	−25.96%	−20.94%	−14.34%	−33.11%
40	−128.87%	−16.79%	−11.38%	−21.31%	−12.09%	−14.70%	−44.78%	−48.95%	−31.31%	−31.44%	−23.74%	−19.09%	−39.06%

Summary and conclusion

Baseball provides an excellent natural laboratory for the study of human ageing because it requires a range of athletic and mental skills, and the play of the game allows for the measurement of individual achievement. Using a longitudinal sample of hitters and pitchers in Major League Baseball from 1921 to 2006, while controlling for many exogenous factors that influence player performances and might inhibit the isolation of the impact of ageing, this study finds that both groups reach peak performance around age 29. Players peak earlier in skills that require more athleticism, and later in those that require less athleticism. Thus, baseball players age in a manner that is consistent with our understanding of human ageing.

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