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**Abstract**
The ultimate goal of any world-class swimmer is to break a record, and technology enables that accomplishment. Using 40 years of data at the individual, national and international level, we identify the quantitative impact that innovation has had on the number of record breaks. We find small but statistically significant impacts on both the number of breaks and the interval between breaks.

**Keywords:** swimming, innovation, technology, record, sports, Poisson, negative binomial

**JEL codes:** O3, L83

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## 1. Introduction

During the Beijing 2008 Olympic Games, swimmers broke twenty-five world records and sixty-six Olympic records, leaving only a single previous Olympic record surviving (Tucker, 2008). While some of that success is clearly due to amazing athletic talent, the goal of this paper is to identify and measure the role that technological innovation has had in speeding up the elite swimmer, and therefore the rate of swimming record breaks.

Many studies have analyzed athletic performance in its most competitive form, most concluding that the development of superior physical performance is in part a result of technological innovation. Although many factors contribute to success in sport, technology appears to be most controversial because it questions the legitimacy of performance times due to its apparent unfair advantage. Entire industries devote their business to the development of sport, as national governments and international corporations annually invest billions in order to sustain public interest in recreation and health (Magdalinski, 2009). As an indicator of optimization, record breaks reflect the rate of change in athletic performance, so this study specifically focuses on the effects of improvements in swimming technology on world and American records broken from 1969-2009.

While sport technology includes body techniques, traditional sport equipment, substances or methods used outside of the competitive setting, to performance-enhancing machines, within this sphere the evolution of competitive swimsuits in particular proves notable (Loland, 2001). It is undeniable that a huge technical jump occurred with the introduction of the first bodysuit, the Adidas JetConcept, which adapted commercial aircraft technology to reduce pool drag and influence how water flows around the swimmer's body. The media has both marveled and criticized the suits' extraordinary light weight, the welded seams, and even the fabric which attempts to mimic the skin of a shark and the shape of a jet, molding the swimmers body into a more streamlined shape (Brenkus, ). Speedo's follow-on innovation, known as Fastskin technology, led to thirteen out of fifteen world records broken that same year at the Sydney 2000 Olympics, where swimmers donning the new suit won eighty-three percent of all medals (Speedo, 2011).

Facilities and equipment have changed remarkably as well. Deeper pools are designed to help absorb wave motion (Speedo, 2011), and Olympic pools are now ten lanes wide for eight swimmers in order to have the outside lanes serve as buffers to keep waves from reverberating. Plastic lane divider buoys redirect water downward instead of outward, and non-skid starting blocks permit faster take-off. Video analysis monitors stroke counts, distance per stroke, split times, and the biomechanics of takeoffs. Critics argue about how technical innovations create an inappropriate advantage for swimmers. This paper aims to impute the size of that advantage over their historical peers.

The following section will review past studies relevant to athletic performance in order to determine which factors are most important in influencing record breaks. Section 3 outlines the data and multivariate regression methodology we use, and the results are presented in Section 4 before the final concluding section offers some limitations and extensions of the current study, along with potential implications.

## 2. Literature

Past research has shown that the demographic and economic characteristics of a country have significant explanatory powers for their athletes' abilities to prosper in athletic competition. Ball (1972) introduced the usage of economic models to determine athletic success, to be followed by other work which emphasized the importance of GDP, income per capita, population, participation, geography, and technological advancements. Most studies (e.g. Bernard and Busse, 2004; Johnson and Ali, 2004; Moosa and Smith, 2004) recognize GDP and income per capita as the best predictors of athletic performance because they measure the resources available to athletes regarding health benefits, training, sponsorships, and infrastructure.

The population of a nation also contributes to athletic success since a larger population size increases success as the nation has a greater talent pool to choose from (Bernard and Busse, 2004; Johnson and Ali; Rathke and Woitek, 2007). Johnson and Ali (2004) estimate how income per capita affects participation, concluding that it costs an average of $260 in GDP per capita to send an athlete to the games, thus richer countries will have more success in sport as they are able to involve more athletes in competition.

Athletic success also depends on the geography of the athlete's nation. Many studies show that colder nations perform better, whether measured by the average number of frost days per winter month (Johnson and Ali, 2004) or the average latitude of the nation (Kuper and Sterken, 2004)

The host nation advantage is well-documented (e.g., Bernard and Busse, 2004; Johnson and Ali, 2004) as a strong factor affecting the outcome of athlete performance as most studies agree it may increase familiarity with infrastructure, influence biased referee calls, offer different events, follow home regulations and time-zone, while also increasing participation and morale with reduced travel costs and more audience support. Other factors analyzed in the literature include political systems (Johnson and Ali, 2004), previous athletic success (Bernard and Busse, 2004), importance and availability of an event to society (Rathke and Woitek, 2007), government expenditure (Moosa and Smith, 2004), the presence of doping (Maennig, 2002), and accurate timing protocols (Munasinghe et al., 2001).

Some studies focus specifically on the role of specific technologic advances in determining success. Kuper and Sterken (2004) focus on the positive impact that technical innovations like the klapskate have on speed skating world records. Similarly, Munasinghe et al. (2001) show how technology maintains the frequency of record breaks in track and field by examining men's records from 1896, while Haake (2009) assesses the effect of technology on Olympic cycling times: of the 221% improvement he documents over 111 years, 45% is accountable to technological improvements.

With respect to swimming in particular, Pyne (2004) uses 676 official race times to show how additional enhancement has improved the performance times of athletes by approximately 0.4%. Tiozzo et al. (2009) prove that bodysuits worn by competitive swimmers improved performance by 1.6% in controlled trials in the 50m crawl race.

## 3. Data and methodology

Data on every one of the 736 individual record breaks over the period 1969-2009 were compiled using USA Swimming (2010) and Magnusson (2010) to document athlete name, nationality, event, gender, performance time, location and date of the break. We also consider the data in aggregated form, summarized into the total number of breaks by year globally (41 observations) and as record counts for the 25 nations to break a swimming record during this period (1025 observations).

Natural-born athletes tend to break many records, often resulting in repeated sport success to specific swimmers. Mark Spitz, Kornelia Ender, and Michael Phelps are partly responsible for the high record breaks in 1972, 1976 and 2009, respectively, so in order to reflect the presence of those athletes, we define a “star athlete” variable which indicates the presence of any athlete that has broken at least three records in any event or year.

As shown in Table 1, nearly thirty records are broken internationally in an average year, but of course, the standard deviation is high and breaks tend to cluster at international competitions, so the average duration between breaks is 20 days.

GDP per capita was calculated for the home nation of each record-breaking athlete, using Shane (2010a) and (2010b). Notice that the high average GDP per capita reflects the fact that poor nations rarely produce record-breaking swimmers, so our results will not be representative of all potential swimmers but only of those who broke a documented record.

Average latitudes for each record-breaking nation were collected by Johnson and Ali (2004) and confirmed by World Latitude and Longitude (2000). Record-breaking swimmers live in colder climates, but also reflects the prominence of the USA (288 records), Germany (154 records), and Australia (103 records) as record-breaking nations. Of course, athletes may not reside at the specified latitude, depending on the size of the country. Again, due to the exclusion of all other competing nations, the estimated impact of latitude will only be accurate within-sample, as we do not have a random collection of participant nations among record-break data.

Table 1: Summary Statistics

| Variable | Obs | Mean | Standard Deviation | Minimum | Maximum |
|---|---|---|---|---|---|
| Total records per year | 41 | 29.51 | 19.91 | 3 | 84 |
| American records per year | 41 | 11.56 | 8.56 | 1 | 39 |
| Day lapse since last record | 735 | 20.24 | 49.13 | 0 | 342 |
| GDP per capita | 736 | 25031.12 | 13685.07 | 28.58 | 52190.78 |
| Latitude | 736 | 42.51 | 9.04 | 11.83 | 63.45 |
| Technologies introduced | 736 | 1.11 | 1.55 | 0 | 5 |

Naturally, there are many factors this study could consider given more data, including the number of official meets offered each year, popularity of the sport, government expenditure on sports (and swimming in particular), individual and team sponsorships, doping regulations, and advances in sports nutrition. We trust that these omitted variables do no bias our results, but have no way to ascertain the impact of their exclusion, given the challenges in quantifying them.

We focus our technological attention on changes in swimsuits and fabrics, including other equipment or facility changes as a control to ensure that we do not inadvertently bias the results of our study. On average, one technology is introduced for every record broken that year, which makes the introduction of five technologies in one year a rare occurrence.

This study focuses on technology as the primary variable of interest, because given the levels of other factors, it should become increasingly difficult for records to be broken in the absence of rare talent or improvement in the elite athlete to improve beyond the level of previous elite athletes. In order to define innovations, we have compiled information on the introduction of a new swimsuit, fabric, or other major relevant innovation since 1969. However, there are serious limitations to our list. First, the value of each technological innovation is impossible to determine objectively without experimental protocols (e.g. Tiozzo et al., 2009). Hence, we are estimating the impact of the average innovation, where the range of improvement might be sizeable. Second, there are potentially omitted innovations that are kept confidential. Third, we implicitly assume that every technology introduced is available to every potential record-breaking athlete, which may not be the case.

A chronology of the major introductions of swimsuits, fabrics and other significant changes is displayed in Table 2. In order to determine the number of swimming technologies introduced every year, information on the release of competitive swimsuits and fabrics were provided by the top swimming company websites such as Speedo, Arena, Nike, Jaked, TYR, and Adidas. Follow-up questions were asked via phone calls with individual company workers. If a new fabric introduced was designed for a specific swimsuit, then both technologies only count once in the total technology column. Furthermore, the table includes the Beijing Water Cube in 2008 due to the abundant records breaks broken in this specific pool. The pool's significance lies in its increased depth and wider lane lines relative to all other pools because it alleviates the reverberations hindering a swimmer's pace (Beijing, 2008).

Table 2 also includes other key innovative technological moments. We discussed the difficulty in defining technique changes, but when FINA publically approved the dolphin kick in competitive swimming, we deemed it necessary to make an exception and include it within the data due to its open release (Berkes, 2008). We also must consider the introduction of the starting block in 2007 as it has proven to

Table 2: Chronology of swimsuit innovations, 1969-2009

| YEAR | SWIMSUIT INTRODUCED | NEW FABRICS | OTHER | TOTAL TECHNOLOGY |
|---|---|---|---|---|
| 1972 | - | Speedo discovers nylon/elastine | - | 1 |
| 1973 | Arena Skinfit | - | | 1 |
| 1975 | - | Speedo discover lycra material | - | 1 |
| 1979 | Arena Flyback | - | - | 1 |
| 1990 | Arena Aqua Racer | - | - | 1 |
| 1993 | - | Speedo S2000 | | 1 |
| 1994 | Speedo Endurance | Speedo Four-Way Stretch | - | 1 |
| 1996 | - | Aquablade | - | 1 |
| 1997 | Arena Xflat | - | - | 1 |
| 1998 | - | - | Adidas introduces body suit concept | 1 |
| 2000 | Speedo Fastskin, Diana Submarine, Nike Lift, TYR Aquapel, Arena Powerskin | - | - | 5 |
| 2001 | - | Speedo FS | - | 1 |
| 2003 | Adidas Jet Concept, TYR Aquashift, Nike Swift | - | - | 3 |
| 2004 | XD Skin, Arena Powerskin Xtreme, Speedo FastskinII, Arena Powerskin X-treme | Speedo FSII | - | 4 |
| 2005 | TYR Fusion | - | Fina allows dolphin kick | 2 |
| 2006 | Speedo Fastskin Pro | - | - | 1 |
| 2007 | - | Speedo FSPRO | FINA allows creation of starting block by Omega | 2 |
| 2008 | TYR Tracer Light, TYR Tracer Rise, Speedo LZR Racer | Speedo LZR Racer Pulse Polyurethane | Beijing Water Cube increases pool depth by 3 meters | 4 |
| 2009 | Arena Powerskin X-Glide, Jaked 01, Adidas HydroFoil, Arena Powerskin R-Evolution | - | - | 4 |

Sources: “Jaked”(2010), Speedo (2011), “TYR” (2010), “Arena History” (2010), authors’ personal phone calls to companies.

shave seconds off of a swimmers race (USA Swimming, 2010). Accurate timing increases the frequency of records because the smaller the unit of reporting, the smaller the margin by which a record must be broken to be recognized especially in short distanced events. Finally, the data set includes the introduction of the body suit concept as the idea itself sparked a flood of new innovations (Feldmann, 2010).

We consider the sea access of a nation (presence of a coastline) to proxy for the popularity of swimming within the nation, but this offers little differentiation within our sample as only five sample countries are completely land-locked: Hungary, Poland, Serbia, Switzerland, and Zimbabwe.

**5. Results and analysis**

Given these data and the previous literature, we propose a simple negative binomial multivariate regression to explain number of record breaks in any given year, since negative binomial distributions effectively represent count data. We will also estimate a Poisson multivariate regression of the time between record breaks, using the Poisson distribution due to its ability to model interval spacing. In each case, we test for and avoid multicollinearity in the variables, and correct for heteroskedasticity issues using White-corrected estimated errors. We test for the presence of autocorrelation using the Durbin-Watson test, but find no cause for alarm once a time trend is included in the analysis.

In the absence of any structural model for this question, we propose a reduced form as:

$$\text{Breaks} = \beta_0 + \beta_1\text{Innovation} + \beta_2\text{Latitude} + \beta_3\text{Stars} + \beta_4\text{GDPpc} + \beta_5\text{SeaAccess} + \beta_6\text{Host} + \beta_7\text{Year} + u \quad (1)$$

$$\text{Duration} = \beta_0 + \beta_1\text{Innovation} + \beta_2\text{Latitude} + \beta_3\text{Stars} + \beta_4\text{GDPpc} + \beta_5\text{SeaAccess} + \beta_6\text{Host} + \beta_7\text{Year} + u \quad (2)$$

where Breaks is the number of record breaks in a year;

Innovation is the number of innovations in a year;

Latitude is the average latitude of the record-breaking athlete;

Stars is the number of athletic stars in a nation in a year;

GDPpc is the Gross Domestic Product per capita of the nation in a year;

SeaAccess is an indicator of whether the nation has a coastline;

Host is an indicator of whether the nation is the host of the record-breaking event;

Year is a time trend; and

u is the unexplained residual of the equation.

Primary results of estimated equations (1) and (2) are presented in Table 3 below. The first three columns model the number of record breaks using a negative binomial distribution, while the remaining two columns model the interval between breaks using a Poisson distribution. Our results have been corrected for heteroskedasticity, and have been suitably tested for multicollinearity and autocorrelation (neither of which is a problem here). The results show equation-wide significance in every case.

Notice first that in every specification, innovation shows up statistically significant with the expected coefficient sign: adding to the number of record breaks, and reducing the interval between record breaks. Innovations appear to contribute an average of roughly 1/3 of a record break per year (a little more for Americans in particular, and an average of 1/6 of a record break per year for the average nation).

Table 3: Primary regression results

| | Number of Annual Record Breaks – Global | | Number of Annual Record Breaks - American | | Number of Annual Record Breaks – Each nation in global competition | | Interval between Record Breaks - Individual | | Interval between Record Breaks - National | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Innovation** | 0.345 | (4.52)*** | 0.396 | (4.83)*** | 0.164 | (3.22)*** | -0.120 | (2.09)** | -0.081 | (5.98)*** |
| **Latitude** | --- | | --- | | $7.99 \times 10^{-3}$ | (0.13) | -0.023 | (2.06)** | -0.003 | (0.95) |
| **Stars** | --- | | --- | | 1.56 | (11.5)*** | 0.094 | (0.49) | -0.190 | (6.21)*** |
| **GDP per capita** | --- | | --- | | $2.23 \times 10^{-6}$ | (0.35) | $-2.24 \times 10^{-6}$ | (0.25) | $6.65 \times 10^{-6}$ | (2.49)** |
| **Sea Access** | --- | | --- | | 0.901 | (3.59)*** | -0.115 | (0.22) | 0.013 | (0.11) |
| **Host nation** | --- | | --- | | --- | | 0.623 | (3.28)*** | --- | |
| **Year** | -0.033 | (4.73)*** | -0.033 | (4.03)*** | --- | | --- | | --- | |
| **Constant** | 68.124 | (4.95)*** | 67.266 | (3.29)*** | -2.719 | (8.32)*** | 3.811 | (5.55)*** | 3.610 | (30.06)*** |
| **Wald $Chi^2$** | (28.76)*** | | (25.13)*** | | (205.39)*** | | (20.04)*** | | (80.11)*** | |
| **Observations** | 41 | | 41 | | 1025 | | 735 | | 1025 | |

*** indicates significance at the 99% level, ** indicates significance at the 95% level, and * indicates significance at the 90% level.

From another perspective, innovation reduces the time between breaks by an average of 0.12 to 0.08 days depending on whether individual or national data are used for the analysis. In other words, the estimated effect of technology is statistically significant, although fairly small in marginal impact.

The coefficients on control variables show up largely as expected. Latitude is only occasionally significant, showing a reduction in the interval between breaks for more Northern athletes. Star athletes strongly increase the number of breaks and reduce the interval between breaks, swamping the size of all other variables in the analysis. Sea access has no significant effect on duration, but appears to speed up record breaks at the national level of analysis. Interestingly, while there is a significant constant rate to the continuous breaking of records in every specification (an interesting effect in itself, suggesting that some athletic improvement is perhaps exogenous), that rate has been decreasing with time once innovation is accommodated (reflecting the fact that breaks become increasingly difficult with the passage of time).

There are a few paradoxes in the results as presented as well. For example, GDP per capita has no significant effect in most specifications, and oddly has a tiny effect to extend the duration between records at the national level. Perhaps this is due to the fact that star athletes frequently hail from (or immigrate to) nations with high GDP per capita. However, the correlation between those two variables is not exceedingly high, at only 0.20.

The host nation effect slows down record breaks as well, an effect which refutes the evidence of previous literature on other types of sporting events. This is not due to the fact that host nations are frequently home to star athletes (correlation 0.02), but remains to be explained by future scholarship.

### 6. Conclusion and extensions

As swimming technology continues to improve, swimming records should keep falling. Part of that pattern is due to technology, but the bulk of it is due to factors outside of our model. While an average of 30 records fall every year, each technological innovation can only be held accountable for 1/3 of one record break per year. If a record break makes the news on average every 20 days, marginal technological change is only responsible for reducing that interval by a tenth of a day.

This does not imply the technology is unimportant, as the cumulative impact can be quite large despite the relatively small marginal effects. The fact that innovation, even measured as crudely as we must, has a measurable impact that is statistically identifiable in every specification presented, is quite surprising.

There are obvious limitations to our study, including the manner in which we identify and measure innovations. For example, to test the robustness of these results, we also attempted to examine the time improvement of each record break as a separate dependent variable, both in absolute terms and as a percentage of the initial record. Our innovation variable was ineffective in all attempts, perhaps because this explanatory variable measures only the existence of an innovation rather than its value in seconds shaved from a record time.

It will be interesting to see how innovations are regulated within competition, given the demonstrable impact on record breaks. The sporting world must balance its dual obligations of providing the highest performance possible for the world to enjoy, while also preserving the purity of the sport for the sake of its main intentions. Record breaks represent the ultimate success in athletics as they continue to shatter barriers deemed impossible by society. Record breaks create a dynamic interaction among fans, athletes, and media in order to maintain the thrill of a sport. While those record breaks are clearly determined by athletes (and especially star athletes), technological innovation clearly has a small but identifiable role as well.

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