On the Age of Elite American Swimmers

by

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Abstract

Several researchers have performed cross-sectional analyses of athletic competition results to estimate the age at *peak performance*. Some of the researchers even drew conclusions about age at *physiological peak* from these analyses. However, such conclusions are problematic if changes in the age of the population are not considered first. We conducted a study of the ages of swimmers competing at the U.S. National Championships between 1985 and 2012 to test for the effects of Olympiad, year-within-Olympiad, sex, event distance, and competitive level. The age of top-level American swimmers (a) has increased over time, (b) is greater in Olympic years than non-Olympic years, (c) is greater for male swimmers than female swimmers, (d) is greater for sprinters than distance swimmers, and (e) is greater for the top-performing swimmers than lower-performing swimmers. These findings help to illustrate the inherent problems with drawing conclusions about physiology from cross-sectional analyses of sport performance data.

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Chapter 1: Introduction

The age at which athletes reach their physiological peak is of interest to researchers, coaches, fans, and of course, the athletes themselves. This information can provide insights into athletic career planning, and more generally, it can aid in our understanding of the performance potential of humans across the lifespan. Several researchers have used the practical approach of examining competition results of top athletes with the goal of drawing conclusions about the age at which athletes reach their physiological peak.

It's likely that the best way to get a true estimate of age at a physiological peak is to conduct a longitudinal study. This approach requires measuring the physiological variable of interest at regular intervals across an individual's life, or at least the years leading up to and after the physiological peak. Because longitudinal studies are particularly time-intensive and difficult to execute, many researchers have used cross-sectional approaches to estimate age at physiological peak. Many of the cross-sectional studies use competition results from athletic contests to estimate age at physiological peak. Sport performance data is convenient for studies of this nature because the data are often readily available and the results often include objective performance measures. The sport of swimming has been particularly useful in this regard because (a) the rules of the sport have changed relatively little in the past century, (b) the competition results make it possible to quantify individual performance, and (c) recent results are readily available online.

There is certainly a great deal that can be learned by using this method to estimate the age at physiological peak in swimming, but there are a few issues with the approach. First, the analysis is cross-sectional and only requires knowing the age at which a single performance occurred. This is problematic because it's not possible to know if the performance represents a peak without additional performance data. Further, even if it were possible to accurately identify the age at peak performance from this method, the age wouldn't necessarily indicate the age at physiological peak. Age at peak performance and age at physiological peak are not one and the same. And they are not necessarily equal. Performance is influenced by numerous physiological, psychological, biomechanical, and socio-environmental factors, so it's not possible to draw conclusions about physiology from the age at peak performance without consideration of the other factors. It's important to keep these variables in mind when examining the literature because failure to do so can lead to some dubious conclusions.

Schulz and Curnow (1988) conducted one of the first studies to attempt to estimate age at peak performance from sport performance data. They used the age of Olympic-gold-medal-winning swimmers to estimate the age at peak performance of these elite athletes. While their main assumption that a swimmer is at his or her performance peak at the time of winning an Olympic gold medal is questionable, the study was important in that it was one of the first to provide such data. Schulz and Curnow used the *1986 Information Please Almanac* to record the age of women and men gold medalist swimmers at each Olympic Games from 1896 to 1980 in sprint (100 meter), middle distance (400 meter), and distance (800 meter for women and 1,500 meter for men) freestyle events. They calculated a mean age of 17.7 years for women and 20.6 years for men, and suggested that the 2.9-year age difference between the sexes was likely biological in nature. In addition, they found that the estimated age at peak performance decreased as event distance increased for both sexes. Importantly, Schulz and Curnow remarked that the age at peak performance changed little across the 84-year time period in question, leading them to speculate that their estimates truly represented age at physiological peak. This conclusion is troubling because Schulz and Curnow drew conclusions about physiology from their cross-sectional analysis without thoroughly considering other factors that could have influenced their findings. It's possible their estimates for the age at peak performance represent nothing more than the age of the oldest swimmers at the time. If so, then their results are indicative of historical socio-environmental constraints, for example, rather than physiological limitation.

The inherent problems with the method used by Schulz and Curnow (1988) are highlighted by the work of Allen, Vandenbogaerde, and Hopkins (2014), who used a longitudinal approach to estimate the age at which swimmers are at their performance peak. They conducted an internet search for the annual best times of the top-16 performers in all swimming events at the 2008 and 2012 Olympic Games as far back as the times were available. This enabled Allen et al. to estimate the age at peak performance of elite women and men swimmers in a variety of events from a statistical analysis of career performance trajectories. Like Schulz and Curnow (1988), Allen et al. estimated that the mean age at peak performance for elite swimmers was older for men (24.2 years) than for women (22.5 years). They commented that the 1.7-year sex difference was comparable to the one found by Schulz and Curnow and speculated that the difference was due to the earlier onset of puberty in girls than in boys. Allen et al.'s findings were also similar to Schulz and Curnow in that the estimated age at peak performance decreased as event distance increased, and suggested that the inverse relationship was due to the development of strength and power for sprint events coming at later ages in swimmers. Despite these similarities, there was an important difference in the findings of the two studies: Allen et al.'s estimates for age at peak performance were about four years older than those of Schulz and Curnow.

There are a number of reasons why the two studies might have generated such different estimates for the age at peak swim performance. Allen et al. (2014) offered the explanation that increases in funding and resources "have allowed top swimmers to forge a career in the sport and thereby continue training and competing to ages closer to their true performance peak than previously possible" (p. 649). In other words, Allen et al. seem to be providing a socio-environmental explanation for why their estimates for age at peak swim performance were older than Schulz and Curnow's (1988) estimates. The suggestion seems to be that Schulz and Curnow analyzed Olympic data prior to 1980, and during this time, there weren't many opportunities or incentives to continue in the sport past the late teenage years, particularly for women. As a result, the best performance happened years earlier than they otherwise would have. Allen et al. analyzed data after increased funding allowed for greater opportunities and incentives for swimmers to train and compete, so the swimmers in their sample were older as were their estimates for age at peak performance. While this hypothesis seems logical, it has not been tested using empirical evidence. The first step in testing the hypothesis is to determine whether or not the age of the elite swim population increased following increased opportunities and incentives to participate in the sport.

This same logic can be applied to conclusions regarding sex and event-distance differences in age at peak performance. Schulz and Curnow (1988) found that men were 2.9 years older than women, while Allen et al. (2014) found a 1.7-year difference between the sexes. Schulz and Curnow had suggested that the explanation for the age difference between men and women was likely biological in nature. Similarly, Allen et al. suggested that the age difference could be explained "almost entirely" by a two-year difference in maturational pace between the sexes, without postulating further as to why their finding of a 1.7-year difference between the sexes was not the same as Schulz and Curnow's finding of 2.9 years. It's certainly possible that the age difference between the sexes is due to physiological differences, but it could also be due to differences in the opportunities and incentives to continue in the sport. If the latter explanation is correct, then we would expect the sex difference in age at peak performance to change along with the age of the elite swim population. The extent to which participation opportunities and incentives have affected age differences between elite female and male swimmers over time has yet to be tested.

With regard to event distance and age at peak performance, Schulz and Curnow (1988) found that there was an inverse relationship for women, but not for men. The mean ages of women gold medalists was 19.4 years for sprinters, 17.6 years for middle distance, and 16.0 years for distance swimmers. Once again, the conclusions drawn from the study were physiological in nature: The age at which athletes reach their performance peak increases as the event in question gets shorter. The cross-sectional nature of their study makes the conclusion tenuous because the performances in their data set were not necessarily the athlete's peak performance; rather, they were performances that were good enough to win an Olympic gold medal. These same findings could also occur if the age of the elite sprint population is older than the age of the elite mid-distance population, which in turn is older than the age of the elite distance population in swimming. Whether or not this is the case is unknown because the age of the elite swim population for different event distances has not been studied to any real extent.

Therefore, the purpose of this study is to analyze the age of the elite American swim population over the course of a 28-year time period to determine whether or not (a) the age of this population has increased, (b) the difference in age between elite female and male swimmers has changed, and (c) the age of elite American swimmers varies with event distance.

Chapter 2: Review of Literature

This review of literature will focus consist of four separate sections: (a) Estimating Age at Peak Performance, (b) Age of Elite Swimmers and Time, (c) Age of Elite Swimmers and Sex, and (d) Age of Elite Swimmers and Event Distance.

Estimating Age at Peak Performance

Investigators have typically used cross-sectional studies to estimate the age at peak performance in humans. The age of elite athletes has been considered, as it is expedient to gather age data of these athletes from the Olympic Games, national competitions, and other events attracting the top performers in their disciplines, which are typically accessible through internet and hard-copy records. In one pioneering study, Schulz and Curnow (1988) gathered data on the Olympic gold medalists in three swimming events between 1896 and 1980 to estimate an age at what they termed "peak performance." However, the age of an athlete at a single competition is not sufficient to presume that the athlete's age amounted to his or her peak performance, even if the athlete earned an Olympic gold medal. It would be better said that the findings of their study amounted to the mean age of Olympic gold medalists for 84 years, or 21 Olympiads, but does not present anything on what might be considered to be the peak physiological performance of the population of elite swimmers.

To attempt to resolve these issues in this method for providing estimates of age at peak performance, investigators could use a longitudinal study whereby the performances of subjects are recorded and analyzed over the lifespan. Ideally, a longitudinal study to determine age at a physiological peak in performance would entail observation of subjects over a lifetime to clearly identify the ascent to peak and decline thereafter. Alternatively, researchers could identify existing elite athletes and track their previous performances to determine the age at which they performed best. Allen, Vandenbogaerde, and Hopkins (2014) sought to identify age at peak performance for the purposes of mapping career performance trajectories, in the interest of youth talent development. In their study of the top 16 performers in every swimming event at the 2008 and 2012 Olympic Games and each of those swimmers' best available annual times, they were also able to estimate the mean age at peak performance for this population.

Data collected and analyzed by such studies are useful in comparing the ages found to be achieved a high-level performance in a sport. Considering additional variables such as time, sex, and event differences can provide insight into whether age has changed as a function of any of these variables, and what implications that might have for considerations of the evolution of human physiology, sports training tactics, technological advances in sport, improved nutrition, and changes in coaching strategies.

Age of Elite Swimmers and Time

Few studies have examined the effect of time on the age of elite swimmers. Most have sought to establish a mean age at peak performance, but few have used statistical analysis to determine the effects of time on age of this population.

Schulz and Curnow (1988) were among the first researchers to use the age of elite swimmers in estimating the relationship of age to peak performance, in their broader study concerning the age of what they termed "superathletes," across a range of disciplines. Using data from the *1986 Information Please Almanac and Who's Who at the Olympics* (1983), they were able to locate the names and birthdates of Olympic gold medalists between 1896 and 1980 for men and women in sprint, middle distance, and distance freestyle events.

Schulz and Curnow were interested in whether the age of these athletes had changed over this 84-year period, and whether this might provide any insights on effects of aging on physiology. Their inclusion of three event distances with different physical demands was an effort to ensure that their estimate of age of Olympic gold medalists in swimming would be representative of all top-performing swimmers regardless of event; they also sought to answer a research question as to whether the age would be the same across different event distances. Similarly, their analysis of the ages of both men and women was intended to answer a research question regarding any differences in age between the sexes.

The most remarkable finding in this study, perhaps, is that Schulz and Curnow (1988) found their estimate of the age of gold medalist Olympic swimmers to be "remarkably consistent" over 84 years. They calculated a mean age of 17.7 years for women and 20.6 years for men. This seems to suggest that as "absolute levels of performance" enhanced over this time period, there weren't effects of aging on physiology that would affect performance outcomes. Rather, Schulz and Curnow suggested that the increases in performance could be attributed to improvements in sports training programs, better equipment, and larger population bases from which to select talent. They found no deviations in age over this time period in "superathletes" coming from other disciplines (track & field, tennis, and baseball), with the exception of golfers.

This landmark study prompted a number of others to estimate the age of elite swimmers. There are a number of reasons why the study by Schulz and Curnow produced the results that it did: It was a cross-sectional study with a relatively small sample size, and perhaps the age of Olympic gold medalists in swimming is not really representative of all elite swimmers. An additional question to consider is whether a single performance by an athlete, even one that results in a gold medal at the Olympics, truly represents that athlete's "peak performance." Without additional performance data on individual athletes, it's impossible to determine whether one performance equates to their highest performance potential or was simply a very good performance at the time. Therefore, Schulz and Curnow did not actually find the "age at peak performance" for elite swimmers, but rather, their ages at the time when they performed well enough to earn a gold medal at the Olympics.

Considering that misleading conclusions may result in any cross-sectional study seeking to examine the effects of age on performance, it seems that a longitudinal study that factors in multiple performances by athletes would yield a better estimate of age at which peak performance is achieved—at least, it will be easier to determine which performances were better than others for a given athlete at certain age. Comparing other estimates of peak performance in elite swimmers may yield information valuable to assessing any changes in age of this population. Allen, Vandenbogaerde, and Hopkins (2014) examined the age-related performance progression for the top 16 performers in all swimming events at the 2008 and 2012 Olympic Games. They used internet searches to find each swimmer's annual best times for as many years as possible, resulting in a total of 6,959 performances for 683 swimmers, and were able to identify the age at which each swimmer achieved their best performance over a period of years. This amounts to a sample size that was 98% greater than that of Schulz and Curnow's (1988) study and included not only the Olympic gold medalists, but the top 16 finishers at the Olympics as well as their annual best times.

While the purpose of their study was to create a tool for mapping career performance trajectories, Allen et al. (2014) had the data available to provide an estimate for mean age at peak performance for this group of elite swimmers. They found that women swimmers included in their study had a mean age of 22.5 years, and men swimmers had a mean age of 24.2 years. This seems to differ significantly from the findings of Schulz and Curnow (1988), who had found mean age estimates of 17.7 years for women and 20.6 years for men who were Olympic gold medalists between 1896 and 1980. What's more, Schulz and Curnow had found that their estimate was "remarkably consistent" over 84 years, and presumably, this estimate should have continued to be consistent or at least close to being consistent such that there wouldn't have been a major deviation over the next 30 years.

There are a number of potential explanations for the increase in age of elite swimmers between the studies, which were published only 26 years apart. The rules governing the sport of swimming have not changed profoundly over at least the past 100 years such that different age-related physiological characteristics would now benefit older swimmers. Regardless of whether a small sample size in the Schulz and Curnow (1988) study affected the validity of their results, the fact remains that Olympic gold medalists in three swimming events between 1896 and 1980 were around four years younger than the top 16 finishers at the 2008 and 2012 Olympic Games at peak performance in their careers. To account for this change in age, Allen et al. (2014) postulated that an increase in resources and funding allowed top performers to stay in the sport until later ages, at which time an age at true physiological peak might be established. In other words, it seems that elite swimmers had necessarily exited the sport at earlier ages due to lack of opportunities to continue training to fulfill their highest potential.

Although the sample size used by Allen et al. (2014) was larger than Schulz and Curnow (1988), it is still limited in that they only considered the peak performance of the top 16 swimmers at two of the Olympic Games, which may not be representative of all competitive swimmers. König, Valeri, Wild, Rosemann, Rüst, and Knechtle (2014) investigated the ages of finalists (top 8 finishers) in all swimming events in additional competitions: at FINA World Championships from 1994 to 2013, and at the Olympic Games between 1992 and 2012. The researchers hypothesized that age of the finalists would be shown to be stable over time, in accordance with the findings of Schulz and Curnow. A total of 3,295 performances by 1,615 women and 1,680 men were examined, and the mean age was calculated separately for each event at the World Championship meets and for the Olympic Games. The main finding was that the age of finalists at World Championships and the Olympic Games has steadily increased over the past 20 years, with the exception of the age of men in the 400-meter freestyle, which has decreased. In the 50-meter freestyle, for example, the age of women increased from 20.0 years in 1994 to 22.3 years in 2014; the age of men increased from 22.6 years in 1994 to 27.7 years in 2014. König et al. noted that a pattern of increasing age and increasing performance over time has been observed in not only swimming, but a number of other sports as well (e.g., running and triathlon), and the researchers suggested that evolution of human anthropometrical characteristics (height, limb length, leanness) might have affected swimming performance. However, they conceded that the time period studied may not have been large enough to identify age progression in swimming with validity.

Buhl, Knechtle, Rüst, Rosemann, and Lepers (2013) examined the age at peak speed of Swiss swimming high scorers between 1994 and 2011 in freestyle and individual medley (IM) events. Time was included as a variable inasmuch as they sought to determine whether the age of elite swimmers in the individual medley and freestyle events had changed over their study time period. Their findings did not indicate any significant differences between the mean ages at peak swim speed between swimmers competing in freestyle and IM events; however, similar to previous studies, they did find significant differences in the mean age between the sexes. More pertinently, they found that the age of swimmers in freestyle and IM events remained unchanged over the time period studied, regardless of event distance. Therefore, their only main finding was that of difference in age between men and women swimmers, but not any differences between swimmers in different events that might owe to differences in age-related specific biomechanical efficiencies. Finally, their finding of unchanged age over the time period from 1994 to 2011 is in line with the findings of Schulz and Curnow (1988).

While most studies have focused on finalists at international or national competitions to determine change in age of elite swimmers over time, Tanaka and Seals (1997) sought to determine the effect of age on physiological functional capacity, using data from top freestyle performances of U.S. Masters swimmers between 1991 and 1995. Since U.S. Masters Swimming limits participants to a certain age range, the study was limited to participants between 19 and 99 years of age. The competition structure in U.S. Masters Swimming competitions is to place swimmers in 5-year increments by age, e.g. 25–29, 30–34, 35–39, etc. Using regression analysis to determine the ages of peak endurance performance in this group, Tanaka and Seals (1997) found that men achieved peak performance times from 25 to 40 years of age, and that woman did the same from 30 to 35 years of age. After these performance peaks, both sexes began to experience a linear decline in performance ability until the age of about 70, and exponential decline thereafter.

In summary, the methodology in determining age at peak performance of swimmers seems to depend on whether the data being used comes from international or national competitions, lists of top performers over a certain time range or results from single competitions at regular intervals, results with any restrictions on age, results that include all swimming events or only selected events, and results that include only top performers or all event entrants in addition to the finalists.

Age of Elite Swimmers and Sex

Age differences between the sexes have been found in several of the aforementioned studies, with most finding an approximately two-year difference between the sexes. Schulz and Curnow found this difference between the sexes (2.9 years) to be remarkably consistent over the time period studied (1896 to 1980). They reasoned that the sex difference in age was "probably biological," in other words, due to the differences in maturational pace between the sexes. Allen et al. (2014) also found a nearly two-year difference (1.7 years), consistent over the time period studied and speculated to be "almost entirely" due to a two-year earlier onset of puberty in women compared with men. Although not explicitly noted by Allen et al., the narrower difference in age between the two studies could also be attributed to the increase in funding and resources that enable top swimmers to stay in the sport—and historically, this may have had a much greater impact on women than on men.

Buhl et al. (2013) had findings similar to that of Schultz and Curnow (1988), with about a two-to-three year difference in age between men and women at peak swim speed. They further postulated that anthropometrical differences between the sexes, i.e., the effect of puberty on percent body fat and lean mass, could have an effect on the biomechanical efficiency in water and explain why the swimming performance of women could be "impaired." This, combined with the age differences at onset of puberty, might explain the approximately two-year difference found in age by sex of elite swimmers. Buhl et al. cited several studies with findings that predictor variables such as limb length and distribution of mass could have an effect, which after puberty might negatively affect women swimmers. König et al. (2014), who found that age differences between the sexes varied by event, also remarked on the possible physiological differences between the sexes as a result of puberty as providing an explanation for the age difference at peak performance. Exploring this further could potentially illuminate interactions between sex and event distance, and the extent thereof, in the age of elite swimmers.

Age of Elite Swimmers and Event Distance

The sport of swimming offers a range of events in which athletes can specialize. In addition to four different competitive strokes, there are differences in event distance, especially within freestyle. In national and international level competition, the range of freestyle event distance ranges from 50 meters to 1,500 meters in pool competition. Elite athletes competing in the 50-meter freestyle finish in around 20 seconds for men and around 23 seconds for women. In the 1,500-meter freestyle, elite men swimmers finish between 14 and 15 minutes and elite women swimmers finish close to 16 minutes. These event distances have much different physiological demands.

Schulz and Curnow (1988) examined the ages of Olympic gold medalists competing in three different swimming events: the 100-meter, 400-meter, and 1,500-meter freestyles. In the sport of swimming, these distances correspond to what are colloquially referred to as "sprint, middle distance, and distance," respectively. While the ages of the gold medalists in each of these events were used to calculate the mean age of all elite swimmers, there were in fact differences found in ages of those competing in the different event distances, specifically an unexpected and seemingly inverse relationship of age to event distance in swimming.

Schultz and Curnow observed that this pattern was the opposite of that which is typical in track events.

Allen et al. (2014) found that both men and women achieved peak performance at later ages in sprint events and at earlier ages in distance events, again suggesting an inverse relationship of age to event distance. They had selected event similar to Schulz and Curnow (1988) to represent the distance categories; sprint was considered to be the 50- and 100-meter freestyle, middle distance was the 200-meter freestyle, and distance were the freestyle events between 400 and 1,500 meters. For men, sprinters had a mean age of 25.0 years, while distance swimmers had a mean age of 22.8 years. Middle distance men swimmers fell in the middle, with a mean age of 24.4 years. Women sprinters had a mean age of 23.3 years, and distance swimmers had a mean age of 21.9 years, with middle distance swimmers again falling in the middle at 22.3 years. Allen et al. theorized that for events demanding greater training loads, like distance freestyle, swimmers become either unwilling or physiologically incapable of sustaining the loads. The potential implication is that distance swimmers might "burn out" from the sport in the form of premature peak or drop-out before they might enjoy a career of the length of a sprinter's. A further suggestion by Allen et al. was that distance swimmers might switch their event focus to shorter distance events.

Rust (2012) found that women reached peak swim speed approximately two years younger than men, but the difference in sex difference decreased with increasing event distance, potentially due to differences in body fat percentage and increase in body buoyancy, benefitting longer distances. Similar findings by Wolfrum et al. (2013) revealed a sex-related difference that significantly decreased with increasing race distance, perhaps due to differences in anthropometric characteristics. This was also reflected by Tanaka and Seals

(1997), who found that the percent sex difference in performance in United States Masters Swimming (USMS) participants aged 19–99 became progressively smaller as the event distance increased, and that magnitudes of decline in all event distances were greater for women than in men. Donato et al. (2003) also found that the magnitude of age-related decline was smaller than that observed in running—this may be a suggestion that, since both running and swimming rely heavily on aerobic conditioning, the differences were not due to training volume but rather with differences in biomechanical technique. This still does not satisfactorily explain why there may be an inverse relationship between age and event distance in swimming or even the extent to which a pattern may be established, but further research is clearly needed to elucidate more clearly the differences in age by event distance in elite swimmers.

Chapter 3: Methods

The purpose of this study was to analyze the ages of elite American swimmers over nearly three decades in order to answer the following research questions:

1. Is the age of elite American swimmers different for the Olympiads since 1985?
2. Is the age of elite American swimmers different for the four years within the Olympiads since 1985?
3. Is the age of elite American swimmers different for men and women since 1985?
4. Is the effect of sex on the age of elite American swimmers different for the Olympiads since 1985?
5. Is age of elite American swimmers different for the sprint, middle distance, and distance freestyle events since 1985?
6. Is the effect of event distance on the age of elite American swimmers different for the Olympiads since 1985?
7. Is there a difference in age between national-level and international-level American swimmers since 1985?
8. Is the difference in age between national-level and international-level American swimmers different for the Olympiads since 1985?

The data for this study were collected from official meet records of the United States Long Course Swimming National Championships for the years 1985 through 2012. This annual competition is typically held in July or August, and it serves as the U.S. Olympic Swimming Trials in Olympic years. The meet results are available online through USA Swimming for the years 1996–1998 and 2005–2012, and in hard copy from the archives at

USA Swimming Headquarters in Colorado Springs, CO, for the years 1985–1995, and 1999–2004. The meet results will be collected from these sources and used for analysis.

Available meet results are complete for men's and women's events with the following exceptions: There is no 800-meter freestyle for men or women in 1992, and it is included for women only in 1986, 1988, 2000, 2004, 2006, and 2008–2012. Results for the 1,500-meter freestyle include men only in 1986, 1988, 1996, 1997, 2000, 2004, 2006, and 2008–2012.

The participants in United States Long Course National Swim Championships include American and international swimmers who achieved the predetermined qualifying standard in at least one event. There are no restrictions on the basis of team affiliation; swimmers can compete as "unattached" if they do not belong to a team. All swimmers' ages as of the first day of competition are included in the results. It's common for swimmers to compete in more than one event at these competitions, and they may swim each event more than once as they compete in the preliminaries (at Olympic Trials), and finals. Only the swimmers who finish in the top eight places in preliminaries qualify for the final (or championship) heat of that event.

In order to answer the research questions, this study will consider two separate dependent variables: the mean age of all American participants competing at the national championship competition (ALL ENTRANTS) and the mean age of swimmers competing in the championship heat in at least one event (FINALISTS). The age of swimmers competing at the U.S. National Championship meets will be included only once per competition in the calculation of ALL ENTRANTS, even if the swimmer competed in multiple events at the meet. Further, although international swimmers are permitted to compete in the U.S. National Championship meets, the age of these competitors will not be included in the calculation of ALL ENTRANTS. Similarly, the age of each swimmer qualifying for a championship heat will be used only once in the calculation for FINALISTS, even if the swimmer qualified for the championship heat in more than one event. International swimmers are not eligible to compete in the championship heat at U.S. National Championship competitions, so their ages will not be considered in the calculation of FINALISTS. As a result, the age of any swimmer who competed in the championship heat in at least one event will be used once in the calculation of ALL ENTRANTS and once in the calculation of FINALISTS.

Four independent variables will be considered: Olympiad, year-within-Olympiad, sex, and event distance. Competitions will be organized into Olympiads to determine whether the age of elite swimmers has changed over time and to what extent. Olympiads are considered to be four-year periods ending with the year of the Olympic Games. For example, the 1988 Olympiad will be the first studied, including the four-year period from 1985 to 1988. There will be seven Olympiads studied: 1988, 1992, 1996, 2000, 2004, 2008, and 2012. Year-within-Olympiad will also be analyzed to determine whether there is a difference in age of elite swimmers depending on when the year falls within each Olympiad, and whether there is an effect of "the Olympic year" on swimmer age. There are four levels for year-within-Olympiad: Year 1, Year 2, Year 3, and Year 4. Using the 1988 Olympiad as an example again, Year 1 is 1985, Year 2 is 1986, Year 3 is 1987, and Year 4 is 1988. Since previous studies have found differences in the ages of elite swimmers by sex and by event distance, the age of swimmers by sex will be analyzed to determine whether there are differences in the ages of men and women. And finally, the age of elite American swimmers will be classified by event distance: sprint events, which will include the 50-meter and 100-

meter freestyle; middle distance events, which will include the 200-meter and 400-meter freestyle; and distance events, which will include the 800-meter and 1,500-meter freestyle. It is common for swimmers to compete, and maybe even final, in more than one sprint, middle distance, or distance event at a given National Championship competition. When this occurs, the athlete's age will only be used once in the calculation of the mean age for the event distance.

Statistical Analysis

The null and alternative hypotheses associated with each of the eight research questions are listed below along with a description of the statistical analysis used to test each null hypothesis. The statistical analyses will be carried out twice for each of the first six research questions, once for the age of national-level American swimmers (i.e., ALL ENTRANTS) and once for the age of international-level American swimmers (i.e., FINALISTS). An alpha level of 0.05 will be used to determine significance for all statistical tests.

Research Question 1. Is the age of elite American swimmers different for the Olympiads since 1985?

H_0: The age of elite American swimmers is the same for the Olympiads since 1985.

H_1: The age of elite American swimmers is different for the Olympiads since 1985.

A three-way (Olympiad by year-within-Olympiad by sex) ANOVA will be used to test this null hypothesis. The decision on whether to reject or fail to reject this null hypothesis will be made on the basis of the F-ratio for the Olympiad main effect, and its associated p-value. If the probability of obtaining the computed F-ratio by chance alone is less than or equal to 0.05, the null hypothesis will be rejected. This will be taken to mean that the age of elite American swimmers is not the same for the seven Olympiads analyzed. In the event that this happens, all pairwise comparisons will be conducted using the Tukey's honestly significantly difference (HSD) post hoc test to determine which pairs of Olympiads differ. On the other hand, if the probability of obtaining the computed F-ratio by chance alone is greater than 0.05, the null hypothesis will not be rejected, and no further analyses will be conducted.

Research Question 2. Is the age of elite American swimmers different for the four years within the Olympiads since 1985?

H_0: The age of elite American swimmers is the same for the four years within Olympiad since 1985.

H_1: The age of elite American swimmers is different for the four years within Olympiad since 1985.

A three-way (Olympiad by year-within-Olympiad by sex) ANOVA will be used to test this null hypothesis. The decision on whether to reject or fail to reject this null hypothesis will be made on the basis of the F-ratio for the year-within-Olympiad main effect and its associated p-value. If the probability of obtaining the computed F-ratio by chance alone is less than or equal to 0.05, the null hypothesis will be rejected. This will be taken to mean that the age of elite American swimmers is not the same for the four years-within-Olympiads analyzed. In the event that this happens, all pairwise comparisons will be conducted using the Tukey's honestly significantly difference (HSD) post hoc test to determine which pairs of years-within-Olympiads differ. On the other hand, if the probability of obtaining the computed F-ratio by chance alone is greater than 0.05, the null hypothesis will not be rejected, and no further analyses will be conducted.

Research Question 3. Is the age of elite American swimmers different for men and women since 1985?

H_0: The age of elite American swimmers is the same for men and women since 1985.

H_1: The age of elite American swimmers is different for men and women since 1985.

A three-way (Olympiad by year-within-Olympiad by sex) ANOVA will be used to test this null hypothesis. The decision on whether to reject or fail to reject this null hypothesis will be made on the basis of the F-ratio for the sex main effect, and its associated p-value. If the probability of obtaining the computed F-ratio by chance alone is less than or equal to 0.05, the null hypothesis will be rejected. This will be taken to mean that the age of elite American swimmers is not the same for the sexes. Since there are only two levels of this independent variable, no post hoc analyses will need to be performed. If the probability of obtaining the computed F-ratio by chance alone is greater than 0.05, the null hypothesis will not be rejected, and no further analyses will be conducted.

Research Question 4. Is the effect of sex on the age of elite American swimmers different for the Olympiads since 1985?

H_0: The effect of sex on the age of elite American swimmers is the same for each Olympiad since 1985.

H_1: The effect of sex on the age of elite American swimmers is different for each Olympiad since 1985.

A three-way (Olympiad by year-within-Olympiad by sex) ANOVA will be used to test this hypothesis. The decision on whether to reject or fail to reject this null hypothesis will be made on the basis of the F-ratio for the Olympiad by sex interaction effect, and its associated p-value. If the probability of obtaining the computed F-ratio by chance alone is less than or equal to 0.05, the null hypothesis will be rejected. This will be taken to mean that there is a significant effect for interaction between sex and Olympiad. If the probability of obtaining the computed F-ratio by chance alone is greater than 0.05, the null hypothesis will not be rejected.

Research Question 5. Is the age of elite American swimmers different for the sprint, middle distance, and distance freestyle events since 1985?

H_0: The age of elite American swimmers is the same for the sprint, middle distance, and distance events since 1985.

H_1: The age of elite American swimmers is different for the sprint, middle distance, and distance events since 1985.

A two-way (Olympiad by event distance) ANOVA will be used to test this null hypothesis. The decision on whether to reject or fail to reject this null hypothesis will be made on the basis of the F-ratio for the event distance main effect, and its associated p-value. If the probability of obtaining the computed F-ratio by chance alone is less than or equal to 0.05, the null hypothesis will be rejected. This will be taken to mean that the age of elite American swimmers is not the same for the three event distances analyzed. In the event that this happens, all pairwise comparisons will be conducted using the Tukey's honestly significantly difference (HSD) post hoc test to determine which pairs of event distances differ. On the other hand, if the probability of obtaining the computed F-ratio by chance alone is greater than 0.05, the null hypothesis will not be rejected, and no further analyses will be conducted.

Research Question 6. Is the effect of event distance on the age of elite American swimmers different for the Olympiads since 1985?

H_0: The effect of event distance on the age of elite American swimmers is the same for the Olympiads since 1985.

H_1: The effect of event distance on the age of elite American swimmers is different for the Olympiads since 1985.

A two-way (Olympiad by event distance) ANOVA will be used to test this null hypothesis. The decision on whether to reject or fail to reject this null hypothesis will be made on the basis of the F-ratio for the Olympiad by event distance interaction and its associated p-value. If the probability of obtaining the computed F-ratio by chance alone is less than or equal to 0.05, the null hypothesis will be rejected. This will be taken to mean that there is a significant interaction between event distance and Olympiad. If the probability of obtaining the computed F-ratio by chance alone is greater than 0.05, then the null hypothesis will not be rejected.

Research Question 7. Is there a difference in age between national-level (ALL ENTRANTS) and international-level (FINALISTS) American swimmers since 1985?

H_0: There is no difference in age between national-level and international-level American swimmers since 1985.

H_1: There is a difference in age between national-level and international-level American swimmers since 1985.

An independent samples *t* test will be used to test the null hypothesis associated with this research question, assuming normal distribution of the variable and homogeneity of variance in the sample. The decision on whether to reject or fail to reject the null hypothesis will be made on the basis of the computed test statistic (*t*), the degrees of freedom, and the p-value. If the probability of obtaining the computed *t* score by chance alone is less than or equal to 0.05, the null hypothesis will be rejected. This will be taken to mean that there is a difference in age between national-level and international-level American swimmers. If the probability of obtaining the computed F-ratio by chance alone is greater than 0.05, then the null hypothesis will not be rejected.

Research Question 8. Is the effect of competitive level on the age of elite American swimmers different for the Olympiads since 1985?

H_0: The effect of competitive level on the age of elite American swimmers is the same for the Olympiads since 1985.

H_1: The effect of competitive level on the age of elite American swimmers is not the same for the Olympiads since 1985.

A two-way (Olympiad by competitive level) ANOVA will be used to test this null hypothesis. The decision on whether to reject or fail to reject this null hypothesis will be made on the basis of the F-ratio for the Olympiad by competitive level interaction, and its associated p-value. If the probability of obtaining the computed F-ratio by chance alone is less than or equal to 0.05, the null hypothesis will be rejected. This will be taken to mean that there is a significant interaction between competitive level and Olympiad. If the probability of obtaining the computed F-ratio by chance alone is greater than 0.05, then the null hypothesis will not be rejected.

Chapter 4: Results

The following research questions were posed for this study and statistical analyses were carried out accordingly. The results are presented below.

Research Question Results

Research Question 1. Is the age of elite American swimmers different for the Olympiads since 1985?

H_0: The age of elite American swimmers is the same for the Olympiads since 1985.

H_1: The age of elite American swimmers is not the same for the Olympiads since 1985.

The null hypothesis above was tested twice, once for FINALISTS and once for ALL ENTRANTS. There were significant main effects for Olympiad for FINALISTS ($F_{6, 1716}$ = 14.24, $p < 0.001$) and ALL ENTRANTS ($F_{6, 13056}$ = 20.59, $p < 0.001$). As a result, the null hypothesis was rejected, which leads to the conclusion that FINALISTS and ALL ENTRANTS were not the same for the seven Olympiads analyzed. Tukey's honestly significantly difference (HSD) post hoc test indicated that the following pairs of Olympiads were significantly different for FINALISTS, as shown in Figure 1: 1988 (19.19 years ± 0.18 SE) is different from 1996 (20.15 years ± 0.18 SE), 2000 (19.94 years ± 0.18 SE), 2004 (20.7 years ± 0.2 SE), 2008 (20.8 years ± 0.18 SE), and 2012 (21.29 years ± 0.19 SE); 1992 (19.86 years ± 0.18 SE) is different from 2008 and 2012; 1996 is different from 2012; 2000 is different from 2012; 2004 is different from 2012; and 2008 is different from 2012. In addition, Tukey's HSD indicated that the following Olympiads were significantly different for ALL ENTRANTS, as shown in Figure 2: 1988 (18.81 years ± 0.09 SE) is different from

2008 (19.49 years ± 0.05 SE) and 2012 (19.64 years ± 0.05 SE); 1992 (19.07 years ± 0.09 SE) is different from 2008 and 2012; 1996 (19.27 years ± 0.07 SE) is different from 2008 and 2012; 2000 (18.95 years ± 0.07 SE) is different from 2004, 2008, and 2012; and 2004 (19.59 years ± 0.07 SE) is different from 2012.

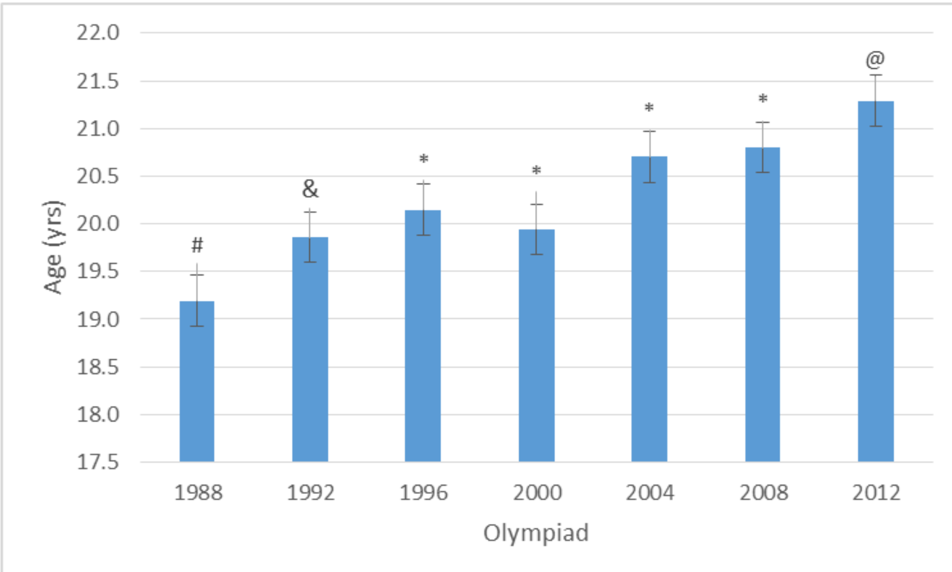

Figure 1. Age (years) of top 8 finishers at U.S. National Championship swim meets (FINALISTS) from 1985 to 2012 as a function of the Olympiad in which the U.S. National Championship meet took place. Note: Bars are means ± 1 SE. # indicates that 1988 is different than 1996, 2000, 2004, 2008, and 2012; & indicates that 1992 is different than 2008 and 2012; * indicates 1996, 2000, 2004, and 2008 are greater than 1988 and 1992; @ indicates that 2012 is different than 1996, 2000, 2004, and 2008.;

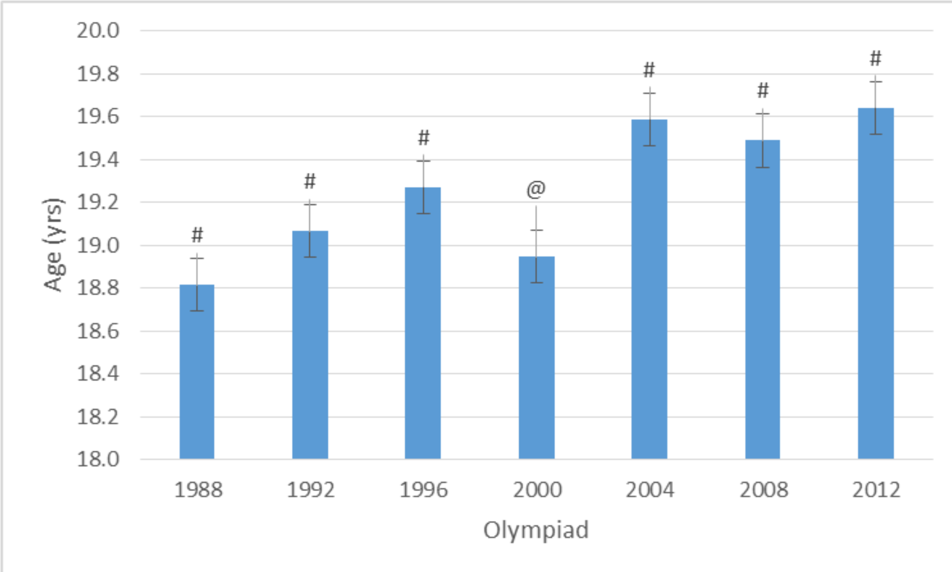

Figure 2. Age (years) of all participants at U.S. National Championship swim meets (ALL ENTRANTS) from 1985 to 2012 as a function of the Olympiad in which the U.S. National Championship meet took place. Note: Bars are means ± 1 SE. # indicates that 2008 and 2012 are greater than 1988, 1992, 1996, and 2004; @ indicates that 2004, 2008, and 2012 are different than 2000.

Research Question 2. Is the age of elite American swimmers different for the four years within each Olympiad since 1985?

H_0: The age of elite American swimmers is the same for the four years within Olympiad since 1985.

H_1: The age of elite American swimmers is not the same for the four years within Olympiad since 1985.

The null hypothesis above was tested twice, once for FINALISTS and once for ALL ENTRANTS. There were significant main effects for year-within-Olympiad for FINALISTS ($F_{3, 1716} = 20.427$, $p < 0.001$) and ALL ENTRANTS ($F_{3, 13056} = 53.158$, $p < 0.001$). As a result, the null hypothesis was rejected, which leads to the conclusion that FINALISTS and ALL ENTRANTS were not the same for Year-within-Olympiad since 1985. Tukey's HSD post hoc test indicated that for FINALISTS, as shown in Figure 3, Year 4 (21.18 years ± 0.14 SE) was greater than Year 1 (19.67 years ± 0.15 SE), Year 2 (20.03 years ± 0.14 SE), and Year 3 (20.08 years ± 0.13 SE). In addition, Tukey's HSD indicated that for ALL ENTRANTS, as shown in Figure 4, Year 4 (19.84 years ± 0.05 SE) was greater than Year 1 (19.01 years ± 0.07 SE), Year 2 (19.04 years ± 0.05 SE), and Year 3 (19.07 years ± 0.05 SE).

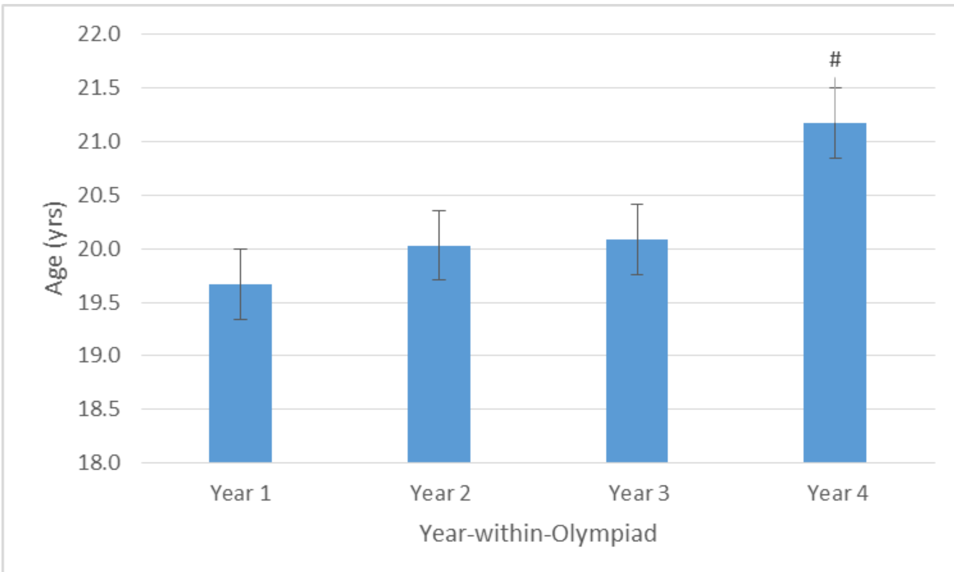

Figure 3. Age (years) of top 8 finishers at U.S. National Championship swim meets (FINALISTS) from 1985 to 2012 as a function of the Year-within-Olympiad. Note: Bars are means ± 1 SE. # indicates Year 4 is greater than Year 1, Year 2, and Year 3.

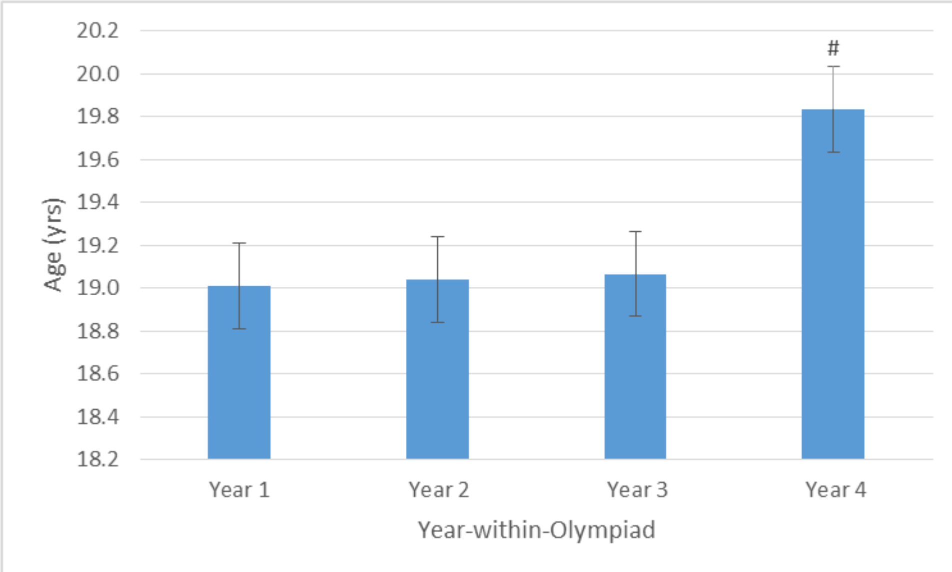

Figure 4. Age (years) of all participants at U.S. National Championship swim meets (ALL ENTRANTS) from 1985 to 2012 as a function of the year-within-Olympiad. Note: Bars are means ± 1 SE. # indicates Year 4 is different than Year 1, Year 2, and Year 3.

Research Question 3. Is the age of elite American swimmers different for men and women since 1985?

H_0: The age of elite American swimmers is the same for men and women since 1985.

H_1: The age of elite American swimmers is not the same for men and women since 1985.

The null hypothesis above was tested twice, once for FINALISTS and once for ALL ENTRANTS. There were significant main effects for sex for FINALISTS ($F_{1, 1716} = 716.161$, $p < 0.001$) and ALL ENTRANTS ($F_{1, 13056} = 179.787$, $p < 0.001$). As a result, the null hypothesis was rejected, which leads to the conclusion that FINALISTS and ALL ENTRANTS were not the same for the two sexes analyzed. FINALISTS was significantly greater for men (21.2 years ± 0.09 SE) than for women (19.32 years ± 0.9 SE), as shown in Figure 5. ALL ENTRANTS was also significantly greater for men (19.99 years ± 0.04 SE) than for women (18.49 years ± 0.04 SE), as shown in Figure 6.

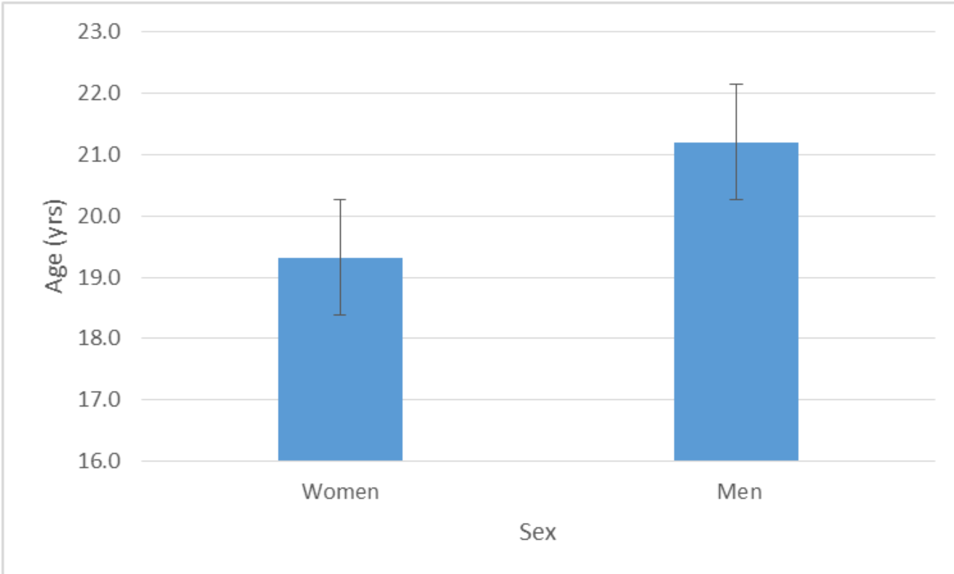

Figure 5. Age (years) of top 8 finishers at U.S. National Championship swim meets (FINALISTS) from 1985 to 2012 as a function of sex. Note: Bars are means ± 1 SE. Men were significantly older than women ($p < .05$).

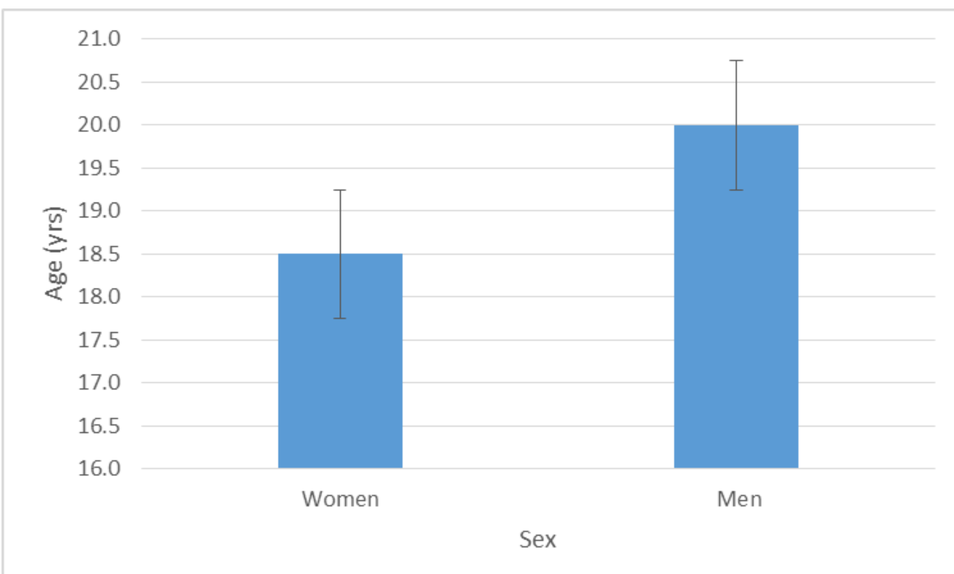

Figure 6. Age (years) of all participants at U.S. National Championship swim meets (ALL ENTRANTS) from 1985 to 2012 as a function of sex. Note: Bars are means ± 1 SE. Men were significantly older than women ($P < .05$).

Research Question 4. Is the effect of sex on the age of elite American swimmers different for the Olympiads since 1985?

H_0: The effect of sex on the age of elite American swimmers is the same for each Olympiad since 1985.

H_1: The effect of sex on the age of elite American swimmers is not the same for each Olympiad since 1985.

The null hypothesis above was tested twice, once for FINALISTS and once for ALL ENTRANTS. There were significant sex by Olympiad interaction effects for FINALISTS ($F_{6, 1716} = 0.995$, $p < .05$), as shown in Figure 7 and ALL ENTRANTS ($F_{6, 13056} = 8.503$, $p < .001$), as shown in Figure 8. As a result, the null hypothesis was rejected, which leads to the conclusion that the effect of sex on the age of elite American swimmers is not the same for the Olympiads since 1985.

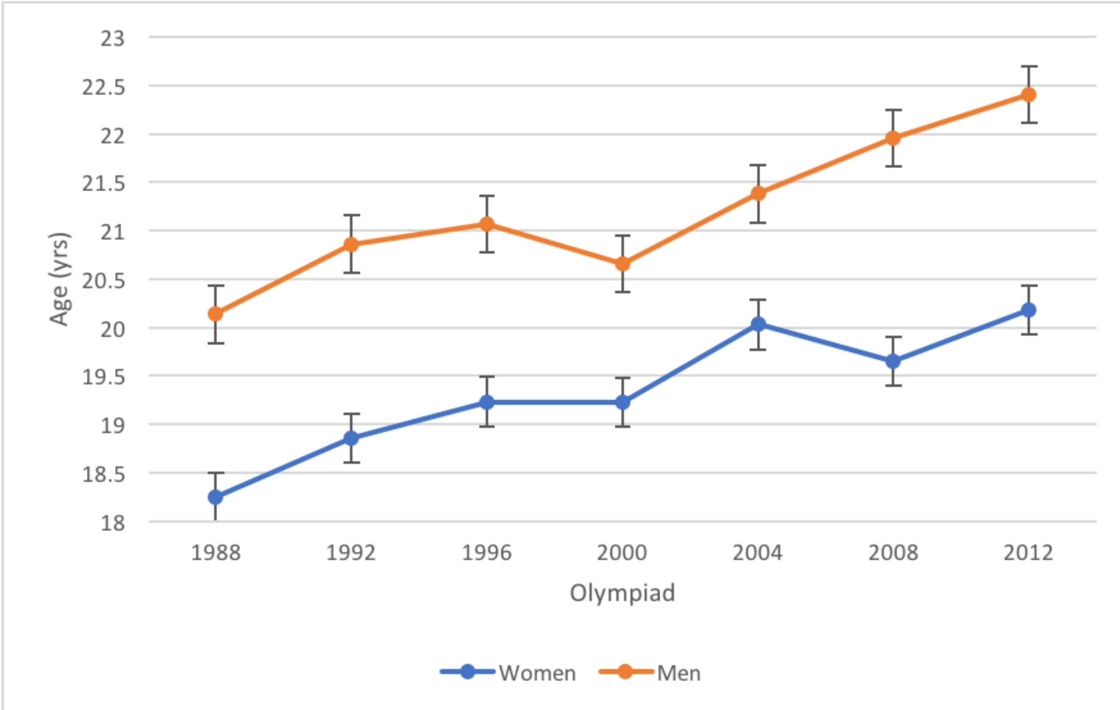

Figure 7. Age (years) of top 8 finishers at U.S. National Championship swim meets (FINALISTS) from 1985 to 2012 as a function of sex and Olympiad. Note: Points represent mean values ± 1 SE. The effect of Sex was different at the different levels of Olympiad ($P < 0.05$).

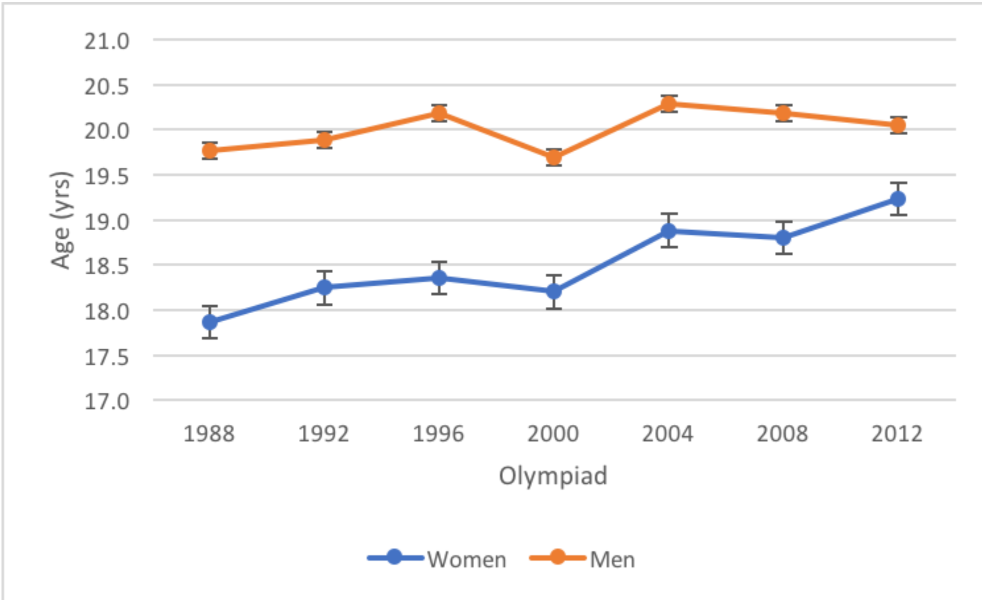

Figure 8. Age (years) of all participants at U.S. National Championship swim meets (ALL ENTRANTS) from 1985 to 2012 as a function of sex and Olympiad. Note: Points represent mean values ± 1 SE. The effect of sex was different at the different levels of Olympiad ($p < .05$).

Research Question 5. Is the age of elite American swimmers different for the sprint, middle distance, and distance freestyle events since 1985?

H_0: The age of elite American swimmers is the same for the sprint, middle distance, and distance freestyle events since 1985.

H_1: The age of elite American swimmers is not the same for the sprint, middle distance, and distance freestyle events since 1985.

The null hypothesis above was tested twice, once for FINALISTS and once for ALL ENTRANTS. There were significant main effects for event distance for FINALISTS ($F_{2, 1716} = 147.166$, $p < .001$) and ALL ENTRANTS ($F_{2, 13056} = 289.456$, $p < .001$). As a result, the null hypothesis was rejected, which leads to the conclusion that FINALISTS and ALL ENTRANTS were not the same for the three event distances analyzed. Tukey's HSD post hoc test indicated that all pairs of event distance were significantly different for FINALISTS, as shown in Figure 9: Sprint (21.86 years ± 0.1 SE), Middle Distance (20.0 years ± 0.1 SE), and Distance (18.92 years ± 0.1 SE). In addition, Tukey's HSD indicated that all pairs of event distance were significantly different for ALL ENTRANTS, as shown in Figure 10: sprint (20.07 years ± 0.04 SE), middle distance (19.27 years ± 0.05 SE), and distance (18.41 years ± 0.05 SE).

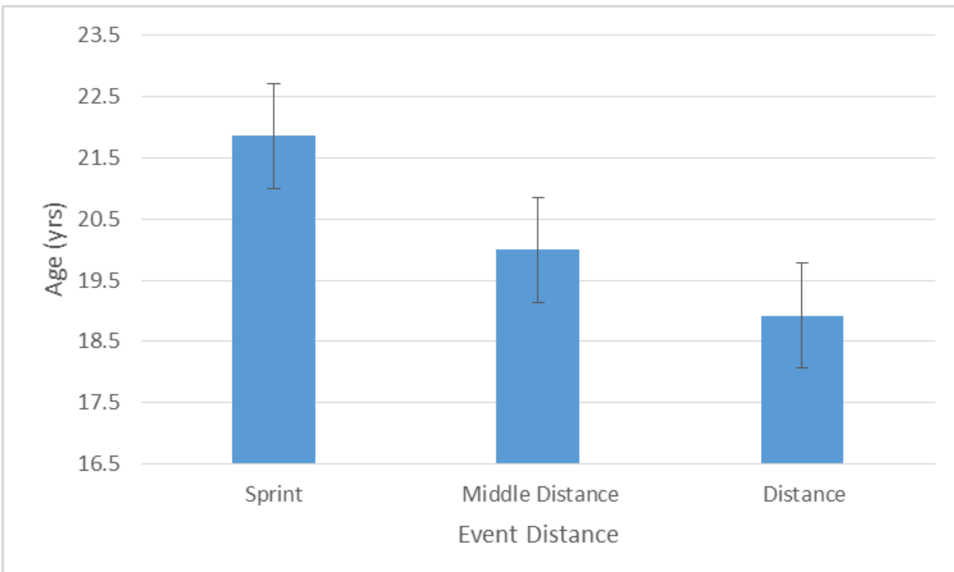

Figure 9. Age (years) of top 8 finishers at U.S. National Championship swim meets (FINALISTS) from 1985 to 2012 as a function of event distance.
Note: Bars are means ± 1 SE. All pairwise event distance comparisons were statistically significant ($p < 0.05$).

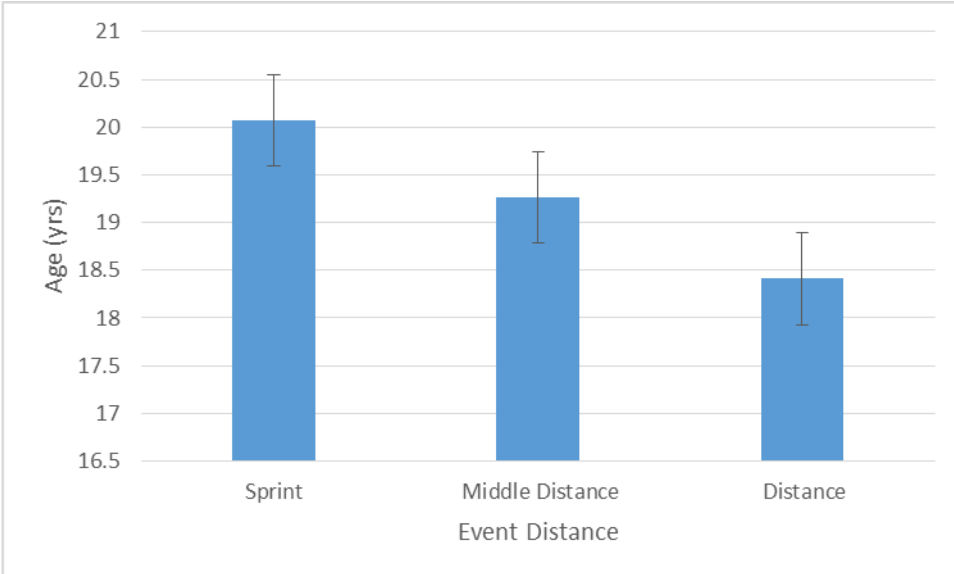

Figure 10. Age (years) of all participants at U.S. National Championship swim meets (ALL ENTRANTS) from 1985 to 2012 as a function of event distance. Note: Bars are means ± 1 SE. All pairwise event distance comparisons were statistically significant ($p < 0.05$).

Research Question 6. Is the effect of event distance on the age of elite American swimmers different for the Olympiads since 1985?

H_0: The effect of Event Distance on the age of elite American swimmers is the same for the Olympiads since 1985.

H_1: The effect of Event Distance on the age of elite American swimmers is not the same for the Olympiads since 1985.

The null hypothesis above was tested twice, once for FINALISTS and once for ALL ENTRANTS. There were significant event distance by Olympiad interaction effects for FINALISTS ($F_{12, 1716} = 2.548$, $p < 0.002$), as shown in Figure 11, and ALL ENTRANTS ($F_{12, 13056} = 2.445$, $p < 0.004$), as shown in Figure 12. As a result, the null hypothesis was rejected, which leads to the conclusion that the effect of Event Distance on the age of elite American swimmer is not the same for the Olympiads since 1985.

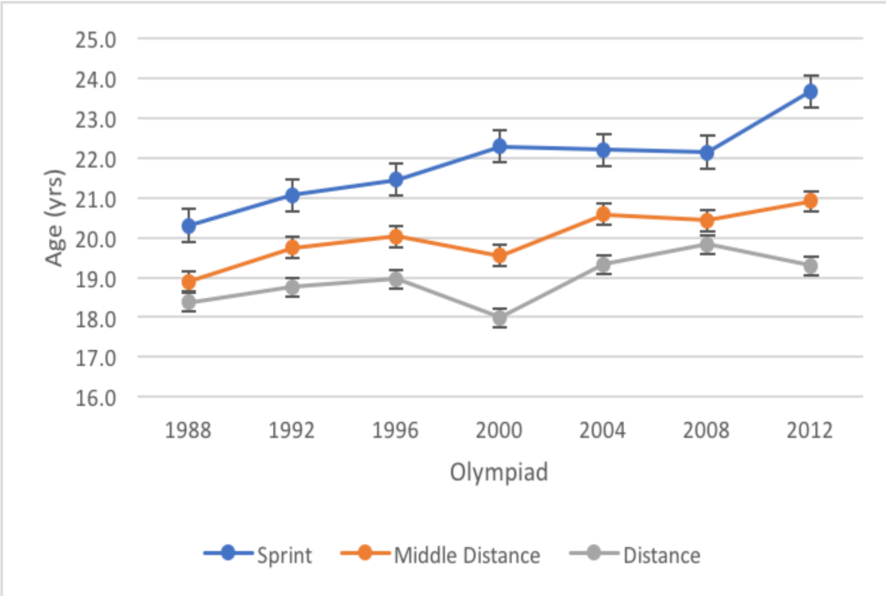

Figure 11. Age (years) of top 8 finishers at U.S. National Championship swim meets (FINALISTS) from 1985 to 2012 as a function of event distance and Olympiad. Points represent mean values ± 1 SE. The effect of Event Distance was different at the different levels of Olympiad ($p < 0.05$).

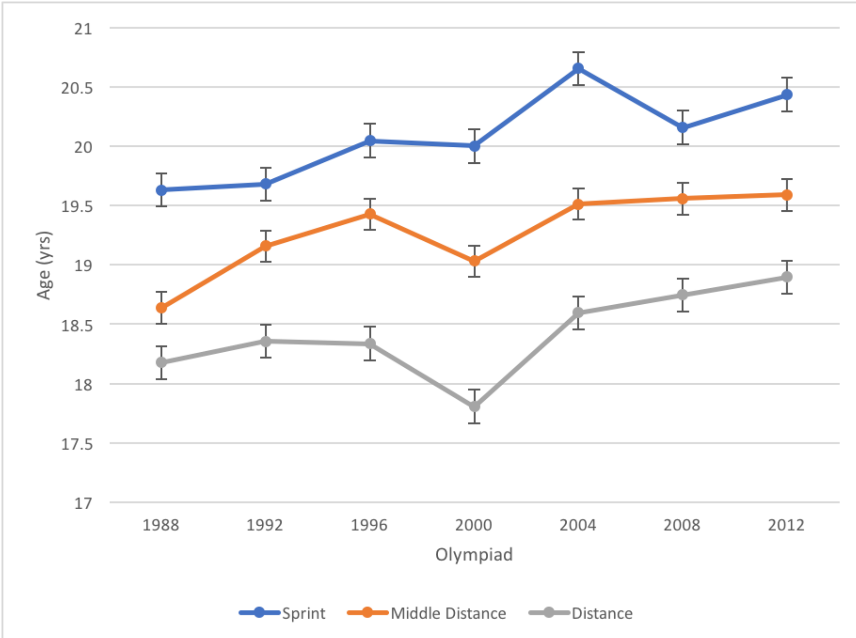

Figure 12. Mean age (years) of all participants at U.S. National Championship swim meets (ALL ENTRANTS) from 1985 to 2012 as a function of event distance and Olympiad. Points represent mean values ± 1 SE. The effect of event distance was different at the different levels of Olympiad ($p < 0.05$).

Research Question 7. Is there a difference in age between national-level (ALL ENTRANTS) and international-level (FINALISTS) American swimmers since 1985?

H_0: Age is the same for national-level and international-level American swimmers.

H_1: Age is not the same for national-level and international-level American swimmers.

There was a significant difference in age between national-level swimmers (ALL ENTRANTS) and international-level swimmers (FINALISTS) ($t_{15094} = 11.80$, $p < 0.001$), as shown in Figure 13. As a result, the null hypothesis was rejected, which leads to the conclusion that there is a difference in age between national-level swimmers (19.37 years ± 0.03 SE) and international-level swimmers (20.33 years ± 0.07 SE).

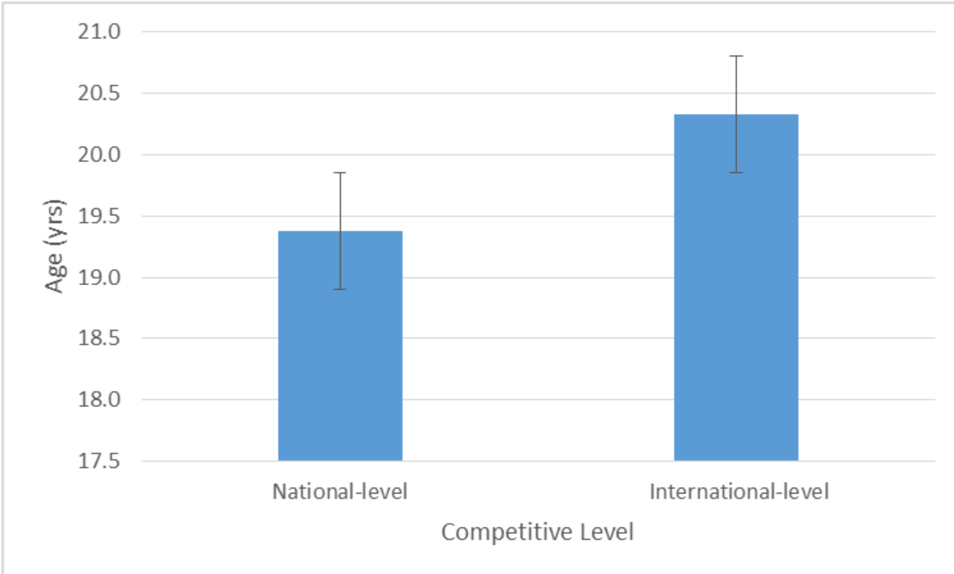

Figure 13. Age (years) of all participants (national-level) and the top 8 finishers (international-level) at U.S. National Championship swim meets from 1985 to 2012. Bars are means ± 1 SE. International-level swimmers were significantly older than national-level swimmers ($p < .05$).

Research Question 8. Is the effect of competitive level on the age of elite American swimmers different for the Olympiads since 1985?

H_0: The effect of competitive level on the age of elite American swimmers is the same for the Olympiads since 1985.

H_1: The effect of competitive level on the age of elite American swimmers is not the same for the Olympiads since 1985.

There were significant competitive level by Olympiad interaction effects ($F_{6, 15082} = 6.85$, $p < .001$), as shown in Figure 14. As a result, the null hypothesis was rejected, which leads to the conclusion that there were significant interactions between Olympiad and competitive level.

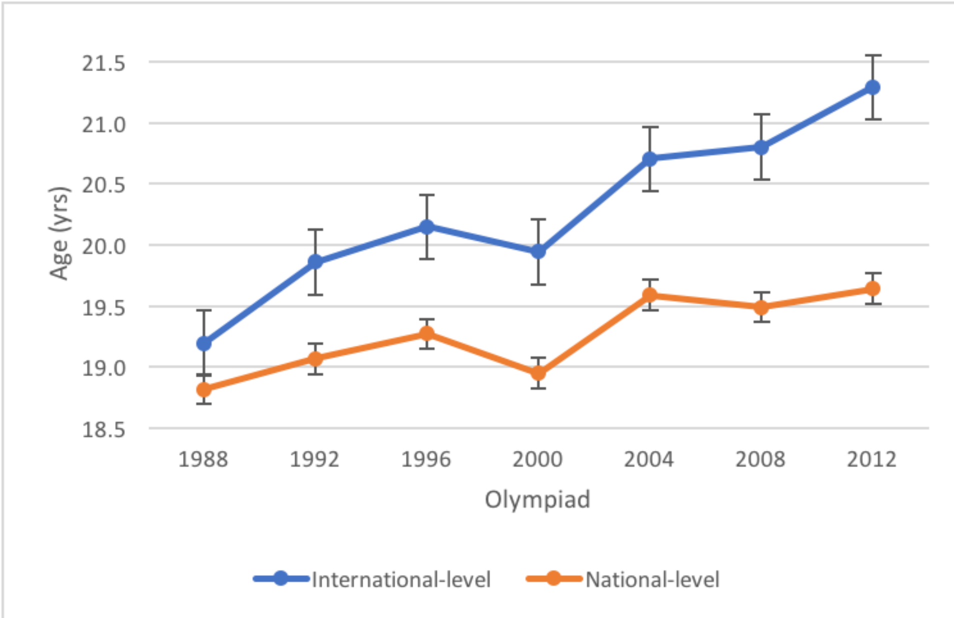

Figure 14. Age (years) of top 8 finishers (International-level) and all participants (National-level) at U.S. National Championship swim meets from 1985 to 2012 as a function of Olympiad. Points represent mean values ± 1 SE. The effect of competitive level was different at the different levels of Olympiad ($p < .05$).

Chapter 5: Discussion

The age at which humans achieve their physiological peak has been of interest to researchers from time immemorial. Researchers have attempted to estimate the age at physiological peak through analysis of sport performance data. Schulz and Curnow (1988) analyzed the ages of Olympic-gold-medal winning athletes in a variety of disciplines to find the age at which elite athletes reach their peak performance. In doing so, they concluded that the age at peak performance (AaPP) was relatively constant from 1896–1980, that AaPP is greater for men than for women, and that AaPP is a function of event distance/duration in certain disciplines. In the years that followed, other researchers (Buhl et al., 2013; Rust et al., 2013; and Wolfrum et al., 2013) used similar approaches to study AaPP and drew similar conclusions. But in addition to using similar methods and drawing similar conclusions, these studies all share a common problem: They are all based on cross-sectional analyses of high-level performance data. Such an analysis could only yield the age at which these elite athletes completed a particular performance on a particular day in a particular year and, as a result, don't necessarily reflect a performance peak. Furthermore, since performance is affected by numerous physiological, psychological, biomechanical, and socio-environmental factors, it's problematic when researchers draw conclusions about physiology from these analyses without consideration of the other factors. Thus, the purpose of this thesis was to analyze the age of the elite-level, American swimming population from 1985 to 2012 in an effort to better understand the inherent problems with drawing conclusion about physiology from cross-sectional analyses of athlete age and performance.

The Age of Elite Swimmers and Time

Schulz and Curnow (1988) were among the first to draw conclusions about physiology from a cross-sectional analysis of the age of Olympic-gold-medal-winning swimmers. Because they found that the age of gold medalists remained the same during the time period studied, they reasoned that the age must represent the age at which elite swimmers reach their physiological peak. Their only independent variable for time was the year of the Olympic Games every four years. We expanded on this model to determine whether the age of swimmers had changed over time, using two independent variables: Olympiad (inter-Olympiad) and year-within-Olympiad (intra-Olympiad).

When we analyzed the age of American swimmers from U.S. National Championship competitions, we found that ALL ENTRANTS and FINALISTS were both significantly older in Year 4 of the Olympiads—i.e., the Olympic year—than in the three years leading up to an Olympic year (see Figures 3 and 4). This finding helps to demonstrate the inherent problems with drawing conclusions about the age at which swimmers reach their physiological peak from cross-sectional analyses of performance data. Doing so in this case leads to the conclusion that athletes reach their physiological peak at older ages during Olympic years. It is, of course, ridiculous to suggest that human physiology changes in a systematic way in Olympic years. An alternative, more plausible explanation is that the Olympic Games provide a greater incentive to continue in the sport—or even come out of retirement—so the age of top-level swimmers is greater during Olympic years.

As previously mentioned, Schulz and Curnow (1988) conducted one of the first studies to attempt to estimate age at peak performance from sport performance data. They determined that the AaPP was 17.7 years for women and 20.6 years for men. Schulz and Curnow remarked that the age at peak performance changed little across the 84-year time period in question, leading them to speculate that their estimates truly represented age at physiological peak. This conclusion is troubling because Schulz and Curnow drew conclusions about physiology from their cross-sectional analysis without thoroughly considering other factors that could have influenced their findings. It's possible that their estimates for the age at peak performance represent nothing more than the age of the oldest swimmers at the time. If so, then their results could be indicative of historical socio-environmental constraints rather than physiological limitation.

If cross-sectional AaPP estimates are sensitive to the age of population under consideration, then it could help us to understand changes in AaPP estimates over time. Again, Schulz and Curnow (1988) estimated AaPP to be 17.7 years and 20.6 years for elite-level female and male swimmers, respectively. Allen et al. (2014), however, found that AaPP was 22.5 years and 24.2 years for elite-level female and male swimmers. suggested that the 1.7-year sex difference was due to the delay in maturational pace. Again, these conclusions represent the age at a high level of athletic competitive performance, not the age at physiological peak. To suggest such a thing would be to say that human physiology changed in the years between these two studies, not to mention in the years separating the other studies utilizing slightly different data sets and methods of analysis. An alternative explanation is that cross-sectional analyses of performance data provide AaPP estimates that are sensitive to the age of the population, and the age of elite-level swimmers changed in the time between the studies by Schulz and Curnow and Allen et al.

Our data support the latter explanation. We found significant main effects of Olympiad on the age of both international-level swimmers (FINALISTS) and national-level swimmers (ALL ENTRANTS), indicating that the age of elite swimmers had increased from 1985 to 2012. For FINALISTS, age increased from 19.19 years in the 1988 Olympiad to 21.29 years in the 2012 Olympiad; for ALL ENTRANTS, age increased from 18.82 years in the 1988 Olympiad to 19.64 years in the 2012 Olympiad.

König et al. (2013) conducted one of the only other studies that examined the change in age of elite swimmers. They focused on the age of finalists at World Championship competitions from 1992 to 2013. König et al. found that the mean age increased for all strokes and distances, except in the women's 200-meter backstroke and men's 400-meter freestyle and 200-meter breaststroke, in which the age had decreased. We examined the age of American swimmers over a greater time period than König et al. (1985-2012 versus 1992-2013) while they studied a higher-performing population of swimmers than we did (all participants and finalists at the U.S. national championships versus finalists at the world championships). Regardless of these differences, the conclusion is the same: The age of the best swimmers has increased over time. Allen et al. (2014) suggested that the increase in age over time was due to increases in funding and resources to allow elite swimmers to stay in the sport to later ages. The implications of this are that swimmers who previously did not have opportunities to continue their careers, due to lack of resources, may now be able to continue training and competing. It's important that researchers studying AaPP understand the changes in the age of the elite-level swim population over time. This is especially true if the researchers are attempting to draw conclusions about physiology from cross-sectional analyses.

Age of Elite Swimmers by Sex

Several researchers have examined whether or not the age at peak performance is different for elite-level female and male swimmers. Schulz and Curnow (1988) and Allen et al. (2014) found differences in age between men and women elite swimmers of 2.9 years and 1.7 years, respectively. Both had suggested that biological differences could explain this difference, but Allen (2014) did not make further suggestions as to why the age gap had narrowed in the time between the studies. Buhl et al. (2013) had findings similar to that of Schultz and Curnow, with about a two-to-three year difference in age between men and women at peak swim speed. They further postulated that anthropometrical differences between the sexes, i.e., the effect of puberty on percent body fat and lean mass, could have an effect on the biomechanical efficiency in water and explain why the swimming performance of women could be "impaired." König et al., who found that age differences between the sexes varied by event, also remarked on the possible physiological differences between the sexes as a result of puberty as providing an explanation for the age difference at peak performance. While it's possible that the differences may be physiological in nature, the findings could also be reasonably explained by the fact that the elite male swim population is older than elite female swim population. in high-level competition in their cross-sectional studies. These data for age by sex for each study are presented in Table 1.

Table 1

Mean Ages (in Years) for Male and Female Elite Swimmers in the Present Study and in Previous Research

Study	**Age—Men**	**Age—Women**	**Difference**
Present study	20.3 ± 2.75	18.8 ± 2.97	1.5
Schulz & Curnow (1988)	20.6	17.7	2.9
Allen et al. (2014)	24.2 ± 2.1	22.5 ± 2.4	1.7
Buhl et al. (2013)	20.9 ± 0.8	18.7 ± 1.0	2.2
Rust et al. (2013)	~22	~19	3.0

If the estimates for age at peak swim performance are influenced by socio-environmental factors, then we might expect the estimates for age at peak performance to change more over the past few decades for women than men. With the advent of Title IX in 1972, women began having more opportunities to compete as high schools and colleges added women's swimming programs to their roster of sports teams. Participation records from the National Federation of State High School Associations (NFHS) show that women's participation in all sports increased from 294,015 to 3.3 million athletes from 1971-1972 to 2014-2015. NCAA participation records, which are available for individual sports, show that the number of female swimmers nearly doubled from 6,218 to 12,356 (compared to 7,746 to 9,455 for men) in the time period from 1981-1982 to 2015-2016. These participation data clearly demonstrate that the opportunities for women to participate in swimming have increase more than for men in recent decades.

The changes in opportunities to participate in swimming likely contributed to the significant interaction effects we detected for FINALISTS and ALL ENTRANTS. In general, there was a clear pattern of increasing age by Olympiad for both sexes, but age tended to increase more for women than men. This is a relatively novel finding, as few researchers examining the age of swimmers have considered the rate of change in age of elite swimmers by sex and over time. Since the earlier findings of Schulz and Curnow (1988) and Buhl (2013) compared to the findings of Allen et al. (2014) and this study indicate a narrowing of the age gap between the sexes, it’s plausible that the ages between the two sexes will continue to narrow. Again, this is likely due to the increase in opportunities to stay in the sport to later ages and the funding made available to international-level performances (FINALISTS).

Age of Elite Swimmers by Event Distance

Previous studies (Schulz & Curnow, 1988; Allen et al., 2014; Wolfrum et al., 2013) found the trend of increasing age with decreasing event distance. Our findings are consistent with the results from the other studies; we found significant main effects for event distance on the age of FINALISTS and ALL ENTRANTS, clearly demonstrating an inverse relationship of event distance with age. The elite distance swimmers in our study were found to be significantly younger than elite middle-distance swimmers, who were significantly younger than sprinters. However, while the relationship between age and event distance is consistent between the studies, the actual ages are not. The age values from Allen et al. are older than those of Schulz and Curnow and the present study. Our explanation for the age differences between the studies goes back to our previous discussion about changes in age over time. Allen et al. produced older estimates for age at peak performance because they studied higher-performing swimmers and conducted their study more recently.

Table 2

Age by Event and Sex, by Study

Study	Sprint	Middle Distance	Distance
Present study**	Women: 19.41 ± 3.3 Men: 21.23 ± 2.9	Women: 18.72 ± 2.7 Men: 20.08 ± 2.5	Women: 17.88 ± 2.5 Men: 19.1 ± 2.3
Allen et al.	Women: 24.74 ± 3.0 Men: 25.6 ± 2.0	Women: 22.3 ± 1.6 Men: 23.2 ± 2.2	Women: 21.9 ± 1.5 Men: 22.9 ± 2.2
Schulz & Curnow	Women: 19.4 ± 2.9 Men: 21.4 ± 3.2	Women: 17.57 ± 1.91 Men: 19.94 ± 2.23	Women: 16.0 ± 1.41 Men: 20.35 ± 3.48

Note: Includes the mean age of ALL ENTRANTS and FINALISTS

While our results regarding age and event distance in swimming are similar to other studies, our interpretation of them is not. Previous researchers provided physiological and biomechanical explanations for the findings. For instance, Schulz and Curnow (1988) suggested that sprinters reach their physiological peak at later ages than distance swimmers because it takes longer for muscle power to develop (Schulz & Curnow, 1988). Donato et al. (2003) argued that biomechanical differences in technique, and not aerobic conditioning, could explain these trends. There is no way to really know for sure if either explanation is true short of taking routine muscle biopsies and repeated biomechanical analyses in high-level swimmers as they age. As we have state previously, the cross-sectional nature of these studies makes the conclusions tenuous because the performances in their data set were not necessarily the athlete's peak performance; rather, they were performances that were good enough to qualify the athletes for the study. Further, these same findings could also occur if the age of the elite sprint population is older than the age of the elite mid-distance population, which in turn is older than the age of the elite distance population in swimming. Our data show that this is the case, and has been for decades.

Competitive Level by Olympiad Interaction

There were significant interaction effects for competitive level by Olympiad, which showed the two groups converging in the 1988 Olympiad and growing gradually further apart approaching the 2012 Olympiad. This means that the age of FINALISTS increased at a greater rate than the age of ALL ENTRANTS, which remained relatively consistent between the 1988 and 2012 Olympiads. Since there are no similar findings published in the literature, it's not possible to determine how these findings might compare. The implications may be that ALL ENTRANTS necessarily drop out of the sport at younger ages, and likely due to lack of opportunities and incentives to continue training and racing. Ambitions of competing in the Olympic Games has always provided an incentive to stay in the sport, and recently, USA Swimming has enacted a financial assistance program for top performers (without constraint due to high school or NCAA eligibility status) to remain in the sport as members of the USA National Swim Team. Swimmers with FINA top-8 times in an event can receive up to $3,000/month; swimmers with times that place them between 9th and 16th can receive up to $2,000/month. Without a ceiling to their potential in the sport, as long as FINALISTS continue to perform well enough to hold a spot on the U.S. National swim team and receive funding, they are free to train and compete until they reach their full potential.

Summary and Conclusions

Previous researchers conducted cross-sectional analyses of sport performance data in an effort to determine the age at which athletes reach peak performance (AaPP); e.g., Schulz & Curnow, 1988; Buhl et al., 2013; Rust et al., 2013; Wolfrum et al., 2013. The researchers also drew conclusions about the age at which athletes reach their physiological peak. We argue that drawing conclusions about physiology from cross-sectional analyses of performance data is problematic, particularly if the age of the athlete population has changed over time or differs between groups. The purpose of this study was to analyze the age of the elite American swim population over the course of a 28-year time period to determine whether or not (a) the age of this population has increased, (b) the difference in age between elite female and male swimmers has changed, and (c) the age of elite American swimmers varies with event distance.

To do so, we obtained and analyzed the official meet records of the United States Long Course Swimming National Championships for the years 1985 through 2012. We focused on two dependent variables: the age of the top performers (FINALISTS) and the age of all performers (ALL ENTRANTS). We were interested in whether or not the dependent variables changed as a function of five independent variables: Olympiad, year-within-Olympiad, sex, event distance, and competitive level.

The main findings were as follows: (a) swimmer age increased over time, (b) swimmers were older during Olympic years than during non-Olympic years, (c) male swimmer were older than female swimmers, (d) ALL ENTRANTS increased to a greater extent for female swimmers than male swimmers during the time period, (e) sprinters were older than middle distance swimmers who were older than distance swimmers, (f)

FINALISTS were older than ALL ENTRANTS, and (g) the difference between FINALISTS and ALL ENTRANTS increased over time. In short, the results of our study demonstrate that the age of top-level American swimmers has changed over time and differs between certain groups.

Researchers have performed cross-sectional analyses of sport performance data, and used the results to estimate the age at peak performance (Schulz & Curnow, 1988; Buhl et al., 2013; Rust et al., 2013; Wolfrum et al., 2013). This is problematic in and of itself because such analyses provide only the average age at which especially good performances were achieved. It's even more problematic when researchers draw conclusions about the age at which humans reach their physiological peak from the AaPP estimates. The problem with doing so is that AaPP is influenced by numerous physiological, psychological, biomechanical, and socio-environmental factors. As a result, it's not possible to draw conclusions about physiology from the age at peak performance without consideration of the other factors.

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