Technology & swimming: 3 steps beyond physiology

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We focus here on the impact of material science in swimming by measuring the impact of the three successive generations of swimsuits on human performance and estimate the upcoming performance drop consecutive to the decision of the FINA to suspend their use. We investigate the recent evolutions of the best performers over the 1990 – 2009 period and demonstrate that three bursts of performances occurred in 2000, 2008 and 2009. The overall observed gains of these bursts exceed 2.0% for both sexes. The drop in performance that may result from this rule change may return to similar levels as seen in 1999.

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The science of engineering materials and the development of materials science during human history have strongly evolved over the past two centuries[1,2]. Other new technological fields such as particle physics, computer science, nanoscience also flourished[3], all leading to innovations that impacted sport. Polymers and metal alloys such as carbon fibres are exemplars of materials now widely used in various disciplines[4]. In 2008, polyurethane made its first appearance in swimming with the use of a new swimsuit generation. The result was a sudden improvement of performances, allowing athletes to go beyond physiological limits that have been nearly reached[5,6]. This study aimed to quantify the gain provided by the three generations of swimsuits introduced in 1999, 2008, 2009 and to estimate the upcoming performance drop in 2010. Using a recently published methodology[7], we analyzed the single best result each year for the world's top ten swimmers from 1990 to 2009 in order to assess the sudden progression trends and quantify the total performance gain.

Materials and methods

We collected the best performance of the world's top ten swimmers every year in 34 swimming events from 1963 to 2009[8-10]. A total of 6790 individual performances were selected from the data spanning the 1990 – 2009 period as they present a complete measure each year.

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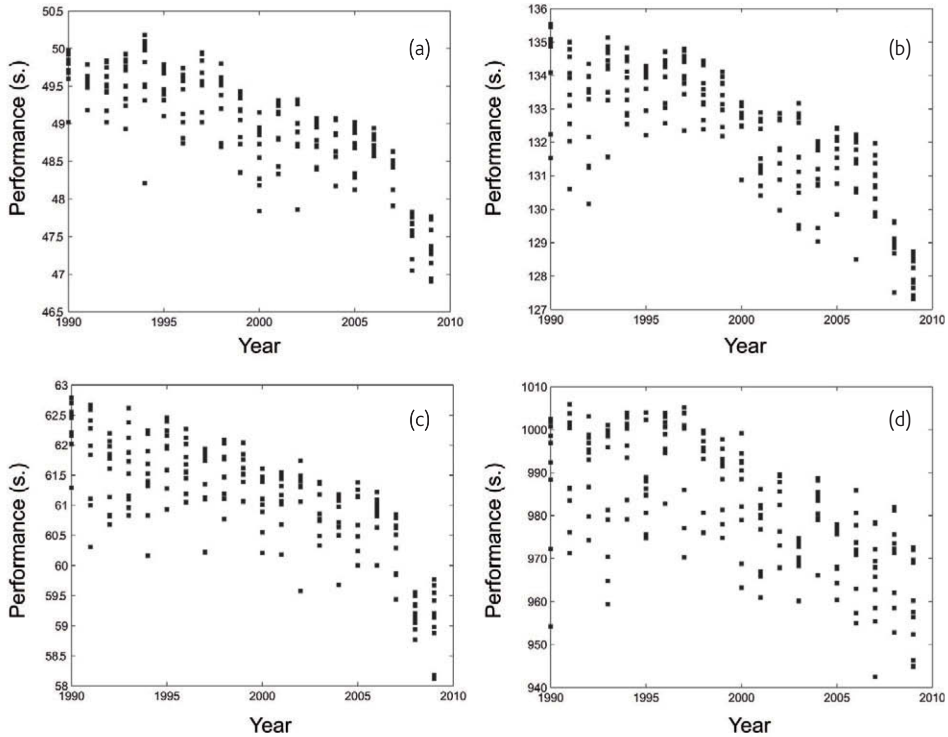

Fig. 1 Four swimming events. (a) Men 200m Breast (b) Men 50m Freestyle (c) Women 100m Back (d) Women 1500m Freestyle (Swimming).

The mean time and standard deviation of the 10 best performances were computed for each year in all events (Fig. 1).

Anova test

An ANOVA test was conducted to estimate the variance of the mean of the 10 best swimmers. This test was intended to study the yearly evolution of performances and to identify any significant sudden development of performances. The test was performed each year between the means from 1990 to 2009 for all events. The number of significant values ($p < 0.05$) was then summed each year for both sexes (Fig. 2).

Performance gains

The relative improvement or "gain" percentage between the mean m of the 10 best from the year t and $t+1$ was defined as:

$$g_t = \left(\frac{m_{t-1} - m_t}{m_{t-1}} \right) \text{x } 100$$

and was computed between all years of all events from 1990 to 2009. To study the overall impact of the three generations of swimsuits in their year of introduction and use, gains obtained in 2000, 2008 and 2009 were summed in one measure by year for all events (overall summed gains) and for each event (summed gains).

The "negative gains" correspond to a performance drop of the mean of the 10 best between the year t and $t-1$.

We analyzed whether swim distance and styles were predictors of summed gain with a linear model (distance and styles separately first and together second). The analysis was performed by gender. Distributions were assumed to be normal. The linear model was performed using MATLAB statistical toolbox.

Predicted performance drop

The prediction of performances drop l_t corresponding to the present ban can be estimated using the relative difference between the mean of top performances in 2009 and the modelling of the previously developed model for the 10 best performances[7]. The model is adjusted to the performances in each event from 1963 to 1999 and extrapolated in 2010. Thus the predicted values are estimated from the physiological period, before the introduction of the swimsuits:

$$l_{2010} = \left(\frac{m'_{2010} - m_{2009}}{m_{2009}} \right) \text{x } 100$$

Where m'_{2010} is the value estimated by the model of the 10 best mean in 2010, m_{2009} is the mean value of the 10 best in 2009.

Results

Anova test

Three peaks of variations are measured in 2000, 2008 and 2009 between the means corresponding to the year of introduction of each swimsuit. The first peak (2000) has a higher number of significant variations recorded for women vs. men (13 vs. 9). The second peak (2008) presents the highest number of variations, with an equal

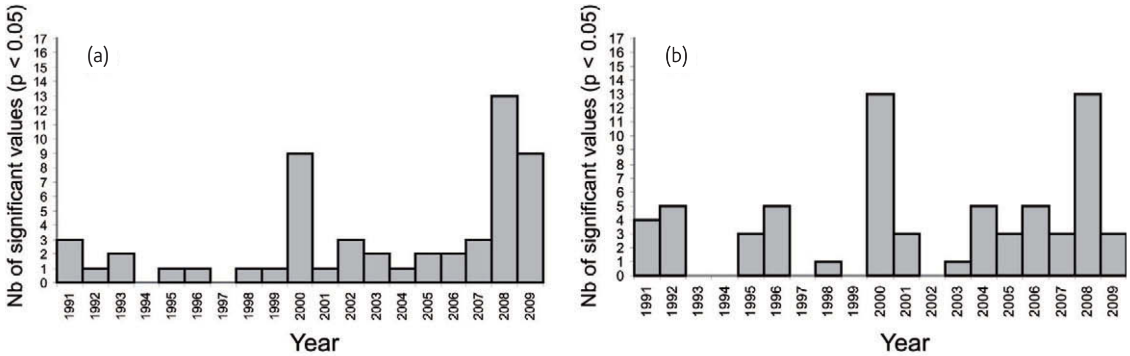

Fig. 2 Number of significant values. (a) for men (b) for women. The number of significant values ($p < 0.05$) of the ANOVA test are plotted by year. Three peaks are visible for men (2000, 2008 and 2009), while only two peaks are visible for women (2000, 2008).

repartition of significant variations between men and women (13). The third peak (2009) shows a high number of variations for men (9) and few variations for women (3).

Performance gains

The gains are given for each event during the year of introduction of each new swimsuit generation (Table 1, Fig. 3). The mean values of gains by year are: 0.74% ±0.26% (2000); 1.16% ±0.48% (2008); 0.68% ±0.55% (2009) for men's events and 1.00% ±0.37% (2000); 0.97% ±0.57% (2008); 0.27% ±0.70% (2009) for women's events. The cumulative mean values for the three years are: 2.58% ±1.29% for men and 2.24% ±1.64%.

Overall summed gains of each events for the three specifics periods are: 12.66% (men, 2001), 19.71% (men, 2008), 11.48% (men, 2009) and 17.06% (women, 2001), 16.50% (women, 2008), 4.59% (women, 2009).

The number of negatives gains are: 0 (2000); 1 (2008); 4 (2009) for men and 0 (2000); 1 (2008); 3 (2009) for women. The nine events concerned are: 800m freestyle men in 2008, 200m fly men (2009), 400m medley men (2009), 400m freestyle men in 2009, 1500m freestyle men (2009), 1500m freestyle women (2008), 200m fly women (2009), 400m medley women (2009) and the 4x100m medley relay women (2009). Gains are also given by gender and distances (Table 1).

The linear model reveals that a relation exists between summed gains and distance (p=0.0048 for men and p=0.0144 for women). Swimming styles show no relations with gains (p=0.6245 for men and p=0.0985 for women).

A sensitivity analysis was then performed without the 1500 meter event and show that the distance effect is less significant in women events (p = 0.08).

Predicted performance drop

The calculated difference with the 1999 asymptote provides a potential drop of 3.65% ±0.78 for all 34 events. The potential drop for men is 3.83% ±0.84; and for women: 3.47 % ±0.70 (Fig. 4, Table 2).

Discussion

The evolution of numerous research fields and the development of technology in the recent era essentially benefited industrialized countries[11]. Technological improvement also helped increase the internationalization of sports meetings, enabling increased competition between nations, and increasing the importance and meaning of sport in society[12]. Today, material science has become a major determinant of victory[13,14]. Here we propose an analysis of the most recent technological enhancements in swimming, i.e. swimsuits, based on the measurement of swimmers' best performances. The analysis of this Olympic discipline was a convenient starting point for the analysis of

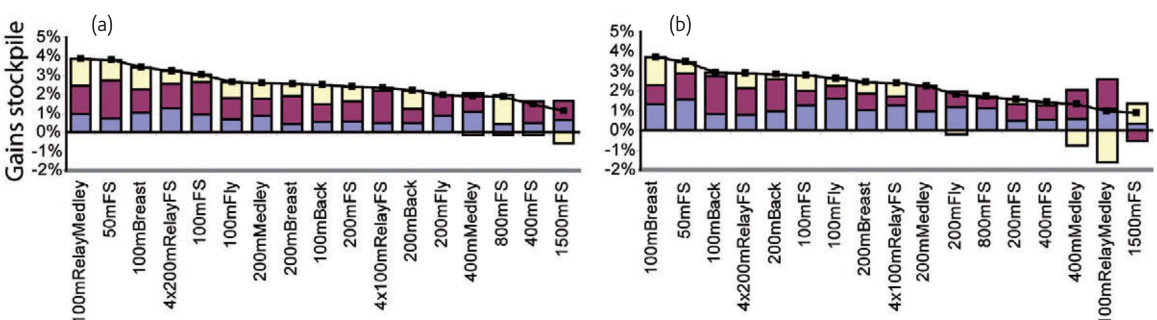

Fig. 3 Gains stockpile. (a) for men (b) for women. The obtained gains for the three swimsuits (1GS blue, 2GS dark red, 3GS light yellow) are stockpiled and sorted by summed gains. The sum of the gain is given for each year (black points and line).

Table 1 Table of gains. Gains are given for each event and each swimsuit in descending order for men and women.

Men				
Event	2000 (1GS)	2008 (2GS)	2009 (3GS)	sum
4x100m relay medley	0.99%	1.48%	1.38%	3.86%
50m freestyle	0.74%	2.02%	1.05%	3.81%
100m breast	1.01%	1.25%	1.16%	3.43%
4x200m relay freestyle	1.30%	1.25%	0.69%	3.24%
100m freestyle	0.93%	1.72%	0.38%	3.02%
100m fly	0.70%	1.12%	0.84%	2.65%
200m medley	0.90%	0.85%	0.87%	2.62%
200m breast	0.44%	1.46%	0.67%	2.57%
100m back	0.56%	0.91%	1.03%	2.51%
200m freestyle	0.60%	1.03%	0.77%	2.39%
4x100m relay freestyle	0.48%	1.73%	0.16%	2.37%
400m freestyle	0.51%	1.14%	0.71%	2.35%
200m back	0.48%	0.74%	0.98%	2.19%
200m fly	0.88%	1.09%	-0.01%	1.95%
400m medley	1.06%	0.99%	-0.14%	1.91%
800m freestyle	0.45%	-0.12%	1.52%	1.85%
1500m freestyle	0.64%	1.04%	-0.57%	1.11%
Women				
Event	2000 (1GS)	2008 (2GS)	2009 (3GS)	sum
100m breast	1.32%	0.97%	1.44%	3.74%
50m freestyle	1.57%	1.35%	0.56%	3.48%
100m back	0.83%	1.93%	0.18%	2.95%
4x200m relay freestyle	0.78%	1.37%	0.73%	2.88%
200m back	1.00%	1.61%	0.25%	2.85%
100m freestyle	1.28%	0.71%	0.80%	2.79%
100m fly	1.63%	0.63%	0.39%	2.65%
200m breast	1.05%	0.80%	0.60%	2.45%
4x100m relay freestyle	1.26%	0.46%	0.68%	2.40%
200m medley	0.97%	1.31%	0.01%	2.28%
200m fly	1.19%	0.79%	-0.18%	1.80%
800m freestyle	1.12%	0.56%	0.06%	1.74%
200m freestyle	0.49%	0.84%	0.24%	1.56%
400m freestyle	0.53%	0.73%	0.18%	1.44%
400m medley	0.59%	1.49%	-0.77%	1.30%
4x100m relay medley	1.10%	1.48%	-1.61%	0.97%
1500m freestyle	0.35%	-0.51%	1.03%	0.87%

the impact of major technological innovations on human performances; the highly controlled conditions of swimming competitions facilitated the measure of this impact.

Swimming speed is limited by the resistive forces of water, also known as drag. They include skin friction, wave, and pressure forces[15-18],

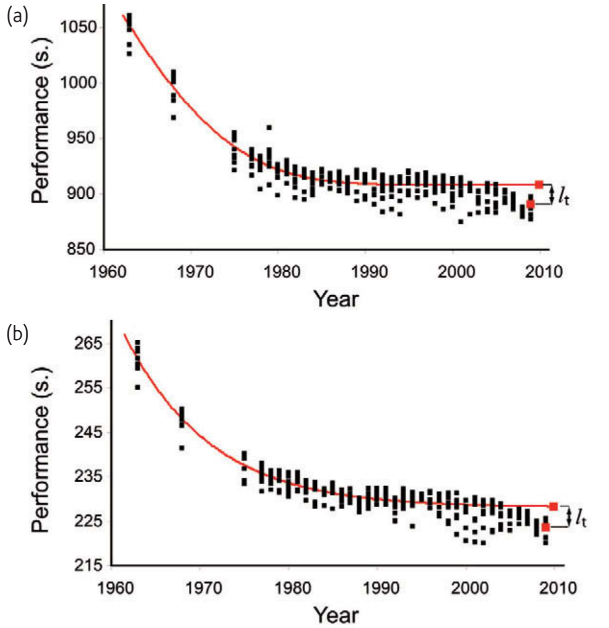

Fig. 4 Predicted Performance drop in (a) 1500m freestyle men (b) 400m freestyle men. The model (red line) is adjusted to the performances (black squares) from 1963 to 1999 and extrapolated in 2010. The estimated performance drop lt is 2.12% for the 1500m and 2.10% for the 400m.

the most relevant force being pressure resistance that generates turbulent flow along the swimmer's body[14,15]. Several studies previously showed that using a swimsuit or wetsuit during effort gave its user an advantage by reducing drag resistance to water flow[19-23]. The first generation swimsuit (1GS) was officially authorized by the FINA in October, 8th 1999[8]. The second generation swimsuit (2GS) was introduced in February, 13th 2008. The third generation swimsuit (3GS) mostly used in 2009 was a derivative of the previous version with an enhancement of the preceding features. The very high number of new World Records (WR) set in a very short time span created controversy as it followed the introduction of the last two generations. FINA decided to suspend the use of swimsuits on January, 1st 2010. On the other hand, it authorized the use of the new angled starting blocks.

According to the analysis of the 10 best performers' swimming times between 1990 and 2009 (Results), three bursts of rapid evolution in a number of swimming events stand out. The evolution of performances was expected to be a smooth progression, as the discipline was part of the first Olympic Games of 1896 along with track and field. To our knowledge, there was no other new ground breaking technique introduced during the studied era, strongly suggesting that each of these bursts corresponds to the introduction of each new suit generation in 2000, 2008 and 2009 respectively.

A higher number of women events were affected by the 1GS than men events (Fig. 2, 4). Furthermore the peak of gains for women occurred in 2000 (Fig. 2). This suggests that the compression of women's body parts (such as the breast) by the swimsuit may have been the key factor reducing drag resistance as early as 2000.

Table 2 Performances drop per event. The performance drop I_{2010} (%) is estimated for each swimming event. The drop is more important on short distances. The given values may correspond to the average expected performance drop of the 10 best swimmers in each event if the FINA decide to draw back all technological enhancements provided since 2000 (including jammers, bodyskins, …).

Event	2010 pred. value	I2010 (%)
4x100m medley relay men	220.58	5.14
50m freestyle men	22.30	4.85
100m back men	54.94	4.60
4x100m freestyle men	199.92	4.49
100m breast women	68.81	4.45
4x100m freestyle relay women	224.83	4.40
50m freestyle women	25.22	4.35
200m medley men	121.34	4.32
100m back women	61.59	4.22
4x200m freestyle relay men	441.68	4.17
100m breast men	61.38	4.15
100m freestyle men	49.29	4.02
200m breast men	133.02	3.87
100m fly men	52.64	3.87
100m freestyle women	55.12	3.84
200m back men	118.71	3.80
100m fly women	59.45	3.73
200m fly men	118.01	3.72
4x200m freestyle relay women	484.84	3.70
200m back women	131.52	3.64
800m freestyle men	480.16	3.61
200m breast women	147.52	3.56
200m freestyle women	119.59	3.42
200m freestyle men	108.12	3.35
200m medley women	134.67	3.33
200m fly women	130.54	3.27
1500m freestyle women	990.28	3.14
400m medley men	257.37	2.96
400m freestyle women	250.10	2.88
4x100 medley relay women	248.54	2.54
400m medley women	282.22	2.35
800m freestyle women	511.98	2.15
1500m freestyle men	908.18	2.12
400m freestyle men	228.36	2.10

Body shape is one of the factors altering drag[15]. For women, this reshaping of the body imparted by the swimsuits may have been the predominant factor, in the technological advancements made since 1999, leading to improved performances.

The introduction of the 2GS in 2008 brought polyurethane to the realm of high level swimming. With an innovative seamless technology, this suit was made of polyurethane woven fabric with a texture based on shark scales[3], resulting in a large reduction of skin friction[3,14,19,24,25]. The 2GS provided an increased number of gains in men and women events (Fig. 2, 3). Its mean impact was 1.2% ±0.5% for men's events and 1.0% ±0.6% for women's events, and had a large effect on all distances and styles (Fig. 3), except on the women's 1500m freestyle and the men's 800m freestyle.

On May 19th 2009, FINA issued a list of 202 swimsuits approved for competition. Some full polyurethane swimsuits, the 3GS, were authorized until January 2010. However the impact of the 3GS on the 10 best performers is less homogeneous than the 2GS. Women showed a lower performance progression (Fig. 2, Fig. 3), while men experienced improvement.

The impact of the three technological leaps due to the introduction of each swimsuit was measured in all events on the chosen years that presented significant variations: 2000, 2008 and 2009. We did not take into account the learning curve following the introduction of these new technologies. Thus, the given technological advances are measured by "default" and may exceed the 2.6% (men) and 2.2% (women) measured here if we consider the entire period 1990 - 2009. Furthermore, the proportion of the swimmers who competed without the swimsuits was not known. This proportion tends to be small but might constitute a bias in our analysis.

The three measured impacts resulted in a larger improvement on short than long distances for both sexes ($p < 0.05$). It suggests the gain provided by the swimsuits may become marginal in long races. The resistance of polyurethane to tension and stretch might be limited on long distances, such as the 1500m freestyle (Fig. 3). Another point is that the number of turns increases with the distance and turns generate hydrodynamic turbulences. It is possible that the swimsuit was not designed to improve speed during tumble turns. The relative improvement may therefore be reduced as distance increases.

Compiling the following year of introduction of the three swimsuits, the average gain in performance improvement ranged from 1.11% to 3.86% for men and from 0.87% to 3.74% for women. Such considerable bursts of performance improvements in 12 months were not observed in any other Olympic discipline in the 1990 – 2009 period. However, similar improvements were observed at the introduction of new Olympic disciplines during the 1896 – 1914 period[5], which may be considered as the athletes' learning curve. In cycling, similar bursts were observed when parallelogram systems (1930's), duralumin or carbon fiber cycles (1980's) were introduced[26]. These bursts are now attributed to technological improvement rather than a learning curve or a physiological development.

The estimated potential drop on the 1990 – 2009 period of 3.7% ±0.8 for the year 2010 was based on the conditions prevailing from 1963 to 1999 (Fig. 4). This value was obtained by modeling the evolution of the 10 best performances from this period[7]. The model was based on a Gompertz function and did not admit any brutal evolution. As the effect induced by the introduction of the swimsuits presented such a profile, we decided to model only the evolution of performances from 1963 to 1999, which follows a more typical physiological curve.

Since 2000, the three successive generations of swimsuits provided high gains along with new world records. At each competition, the media, the audience, the coaches and the athletes were expecting a new world record. Today, with the new FINA regulations, new records will be much more difficult to establish and raises some questions as to how the performance drop might affect the athletes psychologically. However, the estimated potential drops (Table 2) do not take into account the introduction of the new angled starting blocks or the technological innovations that may appear in the new swimsuits. In fact, this computed estimation corresponds to a return in traditional swim briefs, before the introduction of more elaborated swimsuits in the 2000 period. Since the ban of polyurethane swimsuits in 2010, the athletes compete in bodyskins, kneeskins or jammers that still provide a gain as compared to swim briefs. Along with the introduction of the new angled starting blocks, the predicted performance loss may be overestimated. The swimmers may therefore be expected to return to the 1999 – 2007 values. We can make the assumption that the new starting blocks may only increase the initial speed of the swimmers for the three styles in which they are used. The effect may fade with distance, resulting in little impact on performances over long distances. However the use of this new technology and any future technological innovations -whose implementation might be permitted by the FINA-may reduce the expected performance drop after the ban of these three generations of swimsuits in 2010.

The enhancement of performances brought about by technological advances was previously described by Robert Fogel as a "Techno-physiological evolution"[27]. Swimsuits illustrate this process. The cost of one swimsuit is about $400 for one race. With the removal of high tech swimsuits from the sport, the financial investment of each team in each event will likely decrease. The trend observed between 2000 and 2009 could be used to demonstrate the close relationship between funds, technology and performance in this sport.

Conclusion

To our knowledge, no previous study has been published with a precise and comparable quantification of the performance gain provided by the three swimsuit generations. These resulted in bursts of performance including new world records as soon as these technologies were introduced. The present analysis demonstrates the fact that technology has become a major factor increasing human sports performance. It may be our best hope to perform beyond our physiological limits[5,6] while maintaining audience interest. However, the technological enhancement of performance may become limited by the financial costs that are needed to develop and maintain such technology. This questions the ability of sports official authorities to subsidize innovations in a moving economical context. Now that FINA has prohibited these swimsuits, we expect a return to the previous thresholds in 2010, that may be set between the level of the 1999 and 2007 asymptotes, except for the appearance of new technology on authorized jammers and kneeskins swimsuits or around the pools. mt

Acknowledgments

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