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Is a sub 7-hour Ironman™ Possible?

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Abstract

An Ironman™ (IM) triathlon is an event where athletes have to run 3.8, cycle 180 and run 42.2 km. As of 2021, the IM world record time is 7 h 27 min and 53 sec. Hence, people in the triathlon community are starting to wonder whether it would be possible to break the 7-h mark for the distance, and this as soon as in 2022. To the best of our knowledge, we are aware of no theoretical paper which attempted to determine whether the breaking of the 7-h mark is humanly possible. Therefore, the first objective of this article was to determine whether an IM distance triathlon under 7-h might be achieved without external assistance and with the swimming, cycling and running equipment currently available. Our different analyses showed that this is very unlikely, which led to the second goal of this paper that was to demonstrate how external aid could contribute and be used to achieve the breaking of the elusive 7-h mark. First, we made the demonstration that pacers for each sport, through their ability to substantially reduce the aero- and hydro-dynamic drag encountered by the racing triathletes, are an absolute requirement to achieve the targeted swimming, cycling and running times required for a sub 7-h performance. Second, we explain how the wearing of a wetsuit for the swim, the optimization of the cycling equipment and the cycling position to minimize aerodynamic drag on the bike, and the use of carbon fiber plate shoes on the run will contribute to further cut racing time not otherwise possible to achieve with drafting alone. The last aim of this article was to expose the key course characteristics that should be sought by race organizers to optimize the chance of success of this endeavor. The main requirements are a calm body of saltwater, a flat cycling and running courses with a limited number of turns and low temperature, humidity and solar radiation, especially for the run part. The ideal location may be Bahrain in the Persian Gulf since it fits this description, and it is where the current half-IM world record was broken in 2019.

1.   Introduction

An Ironman™ (IM) triathlon is an ultra-endurance event consisting in swimming 3.8, cycling 180 and running 42.2 km. The first ever IM triathlon was held in Hawaii in 1978 and won in a time of 11 h 46 min and 58 sec (Lepers, 2008; Millet et al., 2007). Since then, and especially more so following the first IM event in the continental United States held in Lake Placid in 1999, the IM distance triathlon has grown exponentially in popularity and the best finishing time is significantly faster. To this effect, the men's world record is currently held by the 2008 Olympic champion, Jan Frodeno, who completed the distance in a time of 7 h 27 min and 53 sec, which was achieved in an event specifically designed to break the world record called the *Zwift Tri Battle Royale* (ZTBR). This record was broken on the same year by the 2021 Olympic champion Kristian Blummenfelt in a time of 7 h 21 min and 12 sec at IM Cozumel, but the swim was current-assisted, so it may be argued that this time should not be considered as the world record[1]. On the other hand, the women's world record is held by Chrissie Wellington; she completed the distance in 8 h 18 min and 13 sec.

Just as people wondered if it would be possible to break the 4 min barrier for the mile (Denison, 2006) or the 2 h barrier for the marathon (Hoogkamer et al., 2017; Joyner et al., 2011), people within the triathlon community are starting to wonder whether it would be possible to break the 7-h mark for the IM distance. Projects such as the *Breaking 2* financed by Nike, and the *Ineos 1:59 challenge*, supported by the chemical company Ineos, are events put in place with the goal of creating a hype surrounding an extraordinary sporting feat, which, ultimately, are used by the supporting companies as promotional vehicles and marketing opportunities. Recently, the campaign « *Defy the Impossible* » from which derives the *Sub 8* and *Sub 7 projects*, the latter which represents the main focus of this article, were created with the goal of breaking sometime in 2022 the 7-h barrier for the men and the 8-h barrier for the women for an IM.

We are aware of no scientific writing which attempted to detail from a theoretical point of view whether the breaking of the 7-h mark for the IM is possible. Therefore, the first objective of this article was to elucidate whether an IM distance triathlon under 7-h might be achieved in 2022 without external assistance and with the current swimming, cycling and running equipment. Our different analyses showed that this is very unlikely, which led to the second goal of this paper that was to demonstrate how external aid should be deployed to achieve the breaking of the 7-h mark. The last part of this article is dedicated to race organizers and expose the key course characteristics and meteorological conditions we believe are required to optimize the chance of success of this event.

2.   Is a sub 7-hour IM possible?

Such to determine whether a sub 7-h IM distance triathlon is achievable without any external help and while using the currently available racing equipment, we resorted to a multiple-approach technique where we first analyzed the evolution of the fastest times recorded in the history of the IM since 1989 (prior to 1989, archives related to the IM best times are largely missing). Second, we looked at the progression of the racing times registered at the IM event held in Roth from 1990 to 2019, which is recognized as one of the fastest IM race-course in the world. Third, we summed the best swimming, running and cycling times clocked from all IM races confounded since the inception of the distance. And finally, we predicted the best possible time that could be achieved for the IM distance when

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[1] For the purpose of this article, the time of 7 h 27 min and 53 sec will be considered as the current world record, since the swim was not current-assisted.

doubling the half-IM world record time, while correcting for a computed slowing factor inherent to the doubling of the distance.

2.1   Evolution of the fastest IM times from 1989 to 2021

Table 1 reports the best IM completion times from 1989 to 2021. A time of 7-h would represent an improvement of 6.6% compared to the current world record of 7 h 27 min and 53 sec, which is of considerable importance provided that from 1989 to 2021, the IM world record has only improved by 7.5%, as can be computed from observations made in Table 1. Based on the evolution of the IM world record times over those years, the racing times declined only on average by 1 min 03 sec per year. Figure 1a. illustrates a scatterplot showing the evolution of the IM world record times between 1989 and 2021. The trend of the regression line suggests that there is still room for improving the IM world record time; indeed, over the past 10 years, each new world record has fallen from the previous by an average of ~6 min. Moreover, the time improvement over that time-period has been of ~18 min, compared to ~16 min over the previous 20 years. Interestingly, the regression line predicts that in 2022 the fastest IM time is expected to be between 7 h 39 min and 59 sec and 7 h 26 min and 35 sec., the latter which is 0.3 % faster than the current world record, which was achieved during an event specifically designed to break the previous world record of 7 h 35 min and 39 sec. However, this time is still significantly slower than a sub 7-hour IM. Importantly, based on the calculated trend from the best IM finishing times observed over the past 32 years, a sub 7-h IM completed without external assistance could theoretically not be achieved at least before the year 2049.

2.2   IM Challenge Roth: racing time progression between 1990 and 2019

Table 2 demonstrates the winners' completion times for IM Challenge Roth from 1990 to 2019[2]. The slowest and fastest times achieved over this timespan were respectively 8 h 21 min and 13 sec and 7 h 35 min and 39 sec. Hence, an improvement in time of 10%, or 1 min 30 sec per year was observed over this period of 30 years, which fits nicely well with the results observed regarding the improvement in IM world record times between 1989 and 2021. As shown in figure 1b., a regression line built from the winning times over the past 30 years at IM Challenge Roth demonstrates that the breaking of the 7-h barrier for IM Roth is unlikely to occur at least prior to 2077, based on an associated measurement time error of ± 17 min and 17 sec.

2.3   Summation of the world's fastest Ironman™ swimming, running and cycling times

Another reasonable way to estimate whether a sub 7-h IM is possible without external assistance is to combine and sum the world's fastest IM swimming, cycling and running times ever achieved by any given athletes in any given IM races. Because these times were presumably achieved by discipline specialists and potentially under the best conditions possible, it is very unlikely that even with the best preparation possible a single IM triathlete could align and match or even best those times.

The fastest, non-current-assisted swimming time in an IM triathlon was achieved with a wetsuit, in a lake, by Jan Sibbersen, in a time of 42 min and 17 sec. The fastest official cycling time in an IM, achieved at the ZTBR in 2021 by Jan Frodeno, is 3 h 55 min and 22 sec[3]. Finally, Gustav Iden

[2] The 2021 times are not included since the race course was shorter due to construction work.

[3] The time of 3 h 54 min and 59 sec achieved by American Andrew Starykowicz at IM Florida in 2018 is not considered as the fastest cycling time since the legitimacy of this record is in question because the cycling distance of this triathlon may have been slightly shorter than 180 km.

completed the fastest official IM marathon time (2 h 34 min and 50 sec) in 2021 at IM Florida[4]. The summation of these times, i.e., 7 h 12 min and 29 sec, reveals the fact that even the best times achieved over time within each of the disciplines that make up triathlon would not be sufficient to break the 7-h mark. And one must take into account that this overall time does not include the transition times.

2.4   Prediction of IM time from the Half-IM world record time

The current half-IM world record is held by Kristian Blummenfelt. The Norwegian athlete completed the 2018 Bahrain half-IM in a time of 3 h 29 min and 04 sec. This figure highlights the fact that an athlete looking to break the 7-h mark would need to sustain that pace for twice the distance, which would represent an extraordinary accomplishment. Indeed, by doubling the swimming, cycling and running times a total racing time of 6 h 54 min and 38 sec is obtained[5]. However, as shown in Table 3, when the fastest IM and half-IM times of the current top 20 triathletes in the world competing in both IM and half-IM are compared, it can be observed that, on average, the IM time is 7.3 ± 4.2% slower than the doubling of the half-IM time[6]. Based on our calculations, Blummenfelt's predicted IM time would be 7 h 24 min and 58 sec, with a margin of error of ± 18 min 38 sec. Blummenfelt completed his first IM in 2021 (with a current-assisted swim) with a time of 7 h 21 min and 12 sec. Therefore, in order to break the 7-h barrier, he would need to be 5.9% faster than his predicted time, which is very unlikely considering, as reported above, that the IM world record has only improved by 7.5% over the past 32 yrs.

Based on the computations presented above, we can therefore conclude with relative confidence that a sub 7-h IM is very unlikely to be achieved without external assistance anytime soon. But a question remains: is it even reasonable to believe that an IM under 7-h could be completed with external help. The next part of the article will focus on this given question.

3.   Can a sub 7-hour IM be achieved with assistance?

A prerequisite to the determination that an IM could indeed be achieved at or under a time of 7-h is to first correctly partition the amount of time that should be attributed to each of the single parts of the race, that is the swimming, cycling, running and transition times. We underwent this exercise by contrasting the finishing times for each of the three disciplines in relation to the total finishing times of the winner of the Challenge Roth triathlon from 1990 to 2019. As demonstrated in Table 4, we determined that the swimming, cycling and running times represent, on average, 10.2, 54.9 and 34.9 % of the total completion time of an IM, with a standard deviation for each of the three disciplines ≤ 1%, which underlines the robustness of these observations. Based on those calculations, the targeted time for each discipline would be 42 min and 32 sec for swimming, 3 h 49 min and 32 sec for cycling and 2 h 25 min and 47 sec for running, and the total transition times would need to be less than 2 min. Obviously, faster swimming and cycling times would allow the « racing » triathlete a bigger margin of error to complete marathon before the 7-h mark.

In the next sections, an attempt will be made to demonstrate that with external assistance mostly through drafting during the swimming, cycling and running parts of the race to overcome water or air resistance, a completion time of 7-h for the IM is possible. However, this IM performance would not

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[4] The fastest unofficial marathon time in an IM is 2 h 34 min and 39 sec and it is held by American Matt Hanson and was achieved at IM Texas. However, the legitimacy of the distance is in question.

[5] Doubling the half-IM time and subtracting an average total transition time of 3 min and 30 sec

[6] A factor of 5.4% was calculated by Thorsten Raddle (Trirating, n.d.) by using a total of 107 data points.

be considered an official IM record according to the World Triathlon Corporation rules. Similarly, the sub 2-h marathon achieved by Eliud Kipchoge is not considered eligible as an official world record. In the current paper, « assistance » is defined as any means that an athlete could be using to maximize its swimming, running and cycling velocity, excluding, however, all forms of help coming from water current, a significant negative elevation for the cycling and the run, magnets or equipment running on or requiring a source of energy from the sun, electricity, gazes or batteries.

3.1 Swimming

The fastest non-current-assisted swim time in an IM triathlon was achieved in a lake and with a wetsuit by Jan Sibbersen at IM Frankfurt in a time of 42 min and 17 sec (Trirating, 2021). It is worth highlighting the fact that this athlete has clocked personal best times in a 50-meter pool of 1 min 52 sec for the 200 m, 3 min 56 sec for the 400 m and 15 min 47 sec for the 1500 m (Sailfish, 2021). Taken together, these information show that without a strong background in swimming and the wearing of a wetsuit, an athlete attempting to break the 7-h barrier is very unlikely to achieve the targeted time of 42 min and 32 sec. However, as will be demonstrated below, a strong swimmer capable of achieving a lake- or ocean-based, wetsuit-assisted swimming time of 46-47 min for the 3.8 km distance could potentially achieve this targeted time with the appropriate external help.

3.1.1 Energy cost of swimming

Swimming performance is optimized when propelling cost is maximally reduced. From a pure mathematical standpoint, the energy cost of swimming is calculated by dividing oxygen consumption at a steady state by the corresponding velocity (Zamparo et al., 2005). The energy cost of swimming depends on propelling efficiency, which represents the amount of work necessary to overcome hydrodynamic resistance in relation to the total work required to cover a given distance. Increasing swimming velocity will increase the work necessary to overcome hydrodynamic resistance as the latter increases with the square of the velocity. In addition to the improvement of swimming technique, the wearing of a wetsuit (de Lucas et al., 2000; Peeling & Landers, 2009; Tomikawa et al., 2008; Zamparo et al., 2005) and drafting lead swimmers (Basset et al., 1991; Brisswalter & Hausswirth, 2008; Chatard et al., 1998) have been shown to reduce the work to overcome hydrodynamic resistance and therefore reduce the energy cost of swimming.

3.1.2 Wetsuit

Wearing a wetsuit allows the swimmer to be more horizontal and higher relative to the water surface which, in turn, will act to reduce hydrodynamic resistance (de Lucas et al., 2000; Peeling & Landers, 2009) and the required energy to complete a swimming distance. However, the extent of these effects are dependent upon intrinsic factors related to swimmers such as the swimming technique, propelling efficiency and buoyancy (Chatard et al., 1995). Wearing a wetsuit has been demonstrated to reduce the cost of swimming at 80% of maximal oxygen consumption ($\dot{V}O_{2max}$) by ~7.5 % (Tomikawa et al., 2008) and to increase velocity by ~6% (Gay et al., 2020).

3.1.3 Drafting

A lead swimmer creates a depression in the water behind him, which generates a low-pressure gradient. Therefore, the swimmer drafting a lead swimmer encounters lower resistive body drag (Hausswrith & Brisswalter, 2008). The reduction in drag is estimated to vary between ~10 to 26% (Bentley et al., 2007). Many studies have observed lower lactate levels, ratings of perceived exertion and oxygen consumption when drafting compared to swimming at the same velocity without drafting (Basset et

al., 1991; Chatard et al., 1998). As a result, drafting has been demonstrated to reduce the metabolic cost of swimming by ~5 to 10% and increase velocity by ~3.2 to 6.9% (Bentley et al., 2007). Importantly, the energy saved by drafting a lead swimmer can also have a positive impact on the bike and run portions of the race. Indeed, Delextrat et al. (2003) have observed a 4.8% increase in cycling efficiency after swimming 750 meters at competition pace while drafting a swimmer, compared to without drafting.

Taken altogether, these observations unequivocally illustrate that an acceptable swimming time for an athlete attempting to break the 7-h mark can only be achieved while wearing a wetsuit and using lead swimmers. Considering that the use of drafting could improve swimming performance by an upper limit of 6.9%, then an accomplished swimmer with a demonstrated capacity to swim 46-47 min during an IM should expect to achieve a swimming time in the vicinity of 42 min and 50 sec to 43 min 45 sec with proper drafting.

3.2 Cycling

Cycling is the discipline that is the longest, both in distance and in time in an IM. According to Sousa et al. (2019), it is the part of the race that better predicts the total time to complete the distance ($R^2 = 0.69$; $p < 0.001$), followed by running ($R^2 = 0.52$; $p < 0.001$) and swimming ($R^2 = 0.23$; $p < 0.001$). As reported above, our calculation indicates that in order to break the 7-h barrier a triathlete would need to complete the 180 km cycling distance in a time of 3 h 49 min and 32 sec or faster. This corresponds to a mean velocity of 47.1 km·h^{-1}. In comparison, the fastest official time in an IM is 3 h 55 min and 22 sec (45.9 km·h^{-1}). This would therefore represent an improvement in cycling time of 2.5% compared to the actual fastest cycling time achieved in an IM. As shown in Table 5, the fastest cycling times have improved significantly over the last few years, most probably due to new improvements in technology. In the case of the ZTBR, the use of motorcycles to provide nutrition and hydration, and of a cycling ramp, similar to a velodrome ramp, to allow the triathletes to do a 180º turn without having to slow down, may have been the key contributing factors for the achievement of this fast cycling time.

There are three main resistive forces encountered when cycling that influence the power that a cyclist needs to generate to move forward : 1) rolling resistance, 2) gravity and, 3) air resistance (Crouch et al., 2017; Martin et al., 1998). Reducing to a minimum the impact of these forces on the bike and cyclist is the key for the achievement of fast cycling times. The next sections provide cues on how to minimize the effect of resistive forces while cycling and demonstrate how the use of drafting would permit to perform the 180 km portion of the IM at the velocity required to race a sub 7-h IM.

3.2.1 Rolling resistance and gravity

The wheels are in contact with the road during cycling, which creates resistance. The rolling resistance is affected by the tire pressure and the vertical load applied on the tire. The vertical load is impacted in proportion to the weight of the cyclist and bicycle (Grappe et al., 1999). However, by optimizing the choice of tire and tire pressure and by choosing a bike course with excellent road surface conditions, it is possible to limit the rolling resistance to a minimum. Of course, the ideal race-course should include minimal elevation gains as the force required to move a bike uphill against the force of gravity is substantially more than that required to « fight » rolling resistance or air resistance. On a flat bike course with an ideal road surface condition, the cyclist weight as well as the bicycle weight will have a minimal impact on performance.

3.2.2 Air resistance

The aerodynamic drag (the force applied by the air on an object to resist its motion) depends on the drag coefficient (the efficiency with which an object passes through the surrounding air) and frontal area of the cyclist, the air density and the relative wind speed (Crouch et al., 2017; Griffith et al., 2014). Since aerodynamic drag increases with the square of relative wind speed, as a cyclist goes faster, air resistance becomes a greater factor affecting his rate of forward progression (Faria et al., 2005). At a velocity of 30 km·h⁻¹, air resistance represents about 80% of the resistive force encountered by a cyclist (di Prampero, 2000), and up to 90% of the resistive force at higher velocities (Griffith et al., 2014).

The drag area represents the combination effect (product) of the drag coefficient and frontal area (Barry et al., 2015b). The drag coefficient depends on body geometry and it is lower for streamlined objects such as an airfoil or a car (Barry et al., 2015a). A cyclist should try to reduce its frontal area and streamline his geometry without compromising too much comfort and the ability to generate power. Indeed, about 80% of the aerodynamic drag of a cyclist on a bicycle is due to the cyclist and the remainder is related to the bicycle, the wheels and the accessories such as the water bottle position on the bicycle (Crouch et al., 2017). Small changes to a cycling position, especially to the placement and angle of the handlebars, can reduce the drag area such to confer a 60-sec improvement over a 40 km time trial, which would translate to a 4 min and 30 sec improvement over 180 km (Jeukendrup & Martin, 2001).

Triathletes use bicycles designed to reduce aerodynamic drag. Indeed, they have an aerodynamic frame, handlebars designed for time trialling and lenticular wheels, which, in total, can save about 60 W of power output at a velocity of 50 km·h⁻¹ (Jeukendrup & Martin, 2001). Triathletes competing in IM triathlons do not need to comply with the International Cycling Union (UCI) rules regarding the cyclist position and the cycling equipment (García-López et al., 2008). Therefore, they can optimize their position to reduce their aerodynamic drag as much as possible.

3.2.2 Drafting

Drafting behind another cyclist can significantly reduce air resistance (Blocken et al., 2013), but it is not allowed in IM triathlons. However, if external assistance is used for the *sub7 project*, a group of cyclists could ride in front of the « racing » triathlete which would allow him to ride at a significantly higher speed and reduce energy expenditure, oxygen consumption (Lukes et al., 2005), heart rate, lactate concentration and perceived exertion (Hausswirth et al., 2001). Furthermore, this would allow the « racing » triathlete to run faster after cycling since he would have expended less energy while cycling.

The magnitude of the effect of drafting may depend on many factors, such as the number of cyclists in the group, the position of the cyclists, the distance between each cyclist as well as the drag area of the lead cyclists (Lukes et al., 2005). A cyclist drafting as closely as possible behind a lead cyclist may experience a drag reduction of as much as 15-50%, which may reduce to 10-30% at a distance of one bicycle (Crouch et al., 2017b). Barry et al. (2015) studied the aerodynamic drag of 4 cyclists riding in a time-trial position in a team pursuit position. The four riders experienced, respectively, an average drag saving of 5, 45, 55 and 57% at a speed of 65 km·h⁻¹.

By taking into consideration body weight, equipment weight, coefficient of drag (CDA), air density (Rho), rolling resistance and slope, we estimated the power output required to maintain a velocity of 47.1 km·h⁻¹ (time of 3 h 49 min and 32 sec) without and with drafting (Table 6) (Martin et al., 1998).

For the purpose of illustration, the calculations were done using a body mass of 74 kg and 2 estimated drag coefficients. Based on these numbers, and assuming a conservative reduction in power output of 35-40% due to drafting, the « racing » triathlete would only need to maintain a power output of 198-227 W to progress at a rate of 47.1 km·h^{-1}, which would be significantly less than the power output required if he were to ride without drafting estimated to be between 330 and 349 W. In turn, this highlights the fact that the alternating lead cyclists would have to be capable to sustain that power output. Hence, it must be born in mind that, ultimately, the rate of progression of the « racing » triathlete will be dictated by the quality of the lead cyclists.

3.3   Running

According to our estimation, the IM marathon time would need to be 2 h 25 min and 47 sec, corresponding to a mean velocity of 4.8 m·s^{-1} (17.4 km·h^{-1}) or a pace of 3 min and 27 sec·km^{-1}. This is about 9 min faster (5.8%) than the fastest marathon time ever recorded in an IM (2 h 34 min and 50 sec), which is significant. Among the three main physiological determinants of running performance, which are $\dot{V}O_{2max}$, lactate threshold and running economy (Joyner et al., 2011), the latter is likely to play the most important role (Saunders et al., 2004). It is defined as the rate of oxygen consumption or energy expenditure spent per unit of distance (Hoogkamer et al., 2017; Lacour & Bourdin, 2015). Therefore, an improvement in running economy indicates that less energy is expended for running at a given speed.

Many factors can affect running economy, including body weight, leg architecture, muscle fibers composition (Kyröläinen et al., 2000; Lacour & Bourdin, 2015) and the mechanical and morphological properties of the muscle tendon-units (Albracht & Arampatzis, 2013; Arampatzis et al., 2006; Kubo et al., 2010). Albeit triathletes may exercise a certain control over the first factor, i.e., body weight, they certainly have little influence over the remainder factors which are, for the most part, genetically determined. Moreover, triathletes are generally heavier than elite runners because of the upper body muscles required for swimming which affects their running economy.

Running economy could negatively be impacted after swimming and cycling at a high intensity due to muscle damage (Bessa et al., 2008; Lacour & Bourdin, 2015), neuromuscular fatigue (Lepers et al., 2000), elevated core temperature and possibly dehydration (Hausswirth & Lehenaff, 2001). However, the impact of these factors could be substantially dampened if the « racing » triathlete drafts other cyclists during the cycling part of the race (Bentley et al., 2002). Indeed, under this circumstance, the rate of energy expenditure during cycling would be significantly less, thereby reducing muscle stress and fatigue, the rate of increase in core temperature and subsequently the rate of sweat loss and dehydration.

Running economy will be expected to slowly deteriorate during the marathon (Guezennec et al., 1996; Hausswirth & Lehenaff, 2001; Hausswirth et al., 1996) due to ongoing muscle damage and muscle glycogen depletion (Assumpção et al., 2013). Indeed, based on Brueckner et al.'s (1991) findings, energy expenditure is expected to increase by at least 3% over the course of the marathon. This is due, in part, by a change in the running kinematics, such as a greater forward lean (Hausswirth et al., 1997), an increase in stride time variability (Connick & Li, 2015), a decrease in stride length and an increase in stride frequency (Connick & Li, 2015; Gottschall & Palmer, 2000; Kyröläinen et al., 2000; Place et al., 2004).

Fortunately, there are some tools available to triathletes to minimize the decline in running economy that inevitably occurs during the marathon part of an IM. These are discussed in the following lines.

3.3.1 Running shoes

Running economy can be impacted by the biomechanical advantage provided by shoe technology. Since 1960, when Abebe Bikila ran barefoot to set the world record in 2 h 15 min and 16 sec (Hoogkamer et al., 2017), running shoes have evolved from an ethylene-vinyl acetate (EVA) cushioning to air-cushioned materials. Worobets et al. (2014) observed a 1% improvement in running economy between the Adidas boost midsole and a standard EVA cushioning, which is due to a « superior energy storage/return » in the midsole foam (Hoogkamer et al., 2019a). This energy storage/return effect of the midsole foam compensates for the detrimental impact of the slightly higher shoe weight, compared to a more minimalist shoe or to running barefoot (Hoogkamer et al., 2016; Tung et al., 2014).

Furthermore, high-tech running shoes nowadays have a carbon plate midsole, which improves their binding stiffness. The carbon fiber plate (CFP) has a « clever lever effect » on the ankle joint mechanism and it has a « stiffening effect » on the metatarsophalangeal joint (Cigoja et al., 2021; Hoogkamer et al., 2019b; Nigg et al., 2020). The carbon fiber plate combined with the superior midsole foam result in an improvement in running economy of between 2.8 (Hunter et al., 2019) and more than 4% (Barnes & Kilding, 2019; Hoogkamer et al., 2018), which translates into an improvement in running performance greater than 2% (Muniz-Pardos et al., 2021). Since the introduction of the carbon fiber plate shoes in 2016, all the women's and men's world record in distance ranging from the 5 km to the marathon have been broken (Bermon et al., 2021; Muniz-Pardos et al., 2021).

3.3.2 Drafting

The running energy cost can also be reduced by drafting other runners. Since the running speed is considerably less than the cycling speed, the reduction in energy cost associated with drafting is significantly less with running compared to cycling, but it is still beneficial. Hill (1927) observed that the effect of air resistance when running depended on the air density, the velocity and the projected area of the runner (cited by Pugh, 1970). Pugh (1970) studied the effect of different wind speeds on the running cost. He observed that when the headwind speed increased from 0 km·h^{-1} to 16.2 km·h^{-1} and to 66 km·h^{-1}, the $\dot{V}O_2$ of a runner running at 15.9 km·h^{-1} increased from 2.9 L·min^{-1}, to 3.1 L·min^{-1} and to 5.0 L·min^{-1}, respectively. Pugh (1971) also observed that at a speed of 6 m·s^{-1} (21.6 km·h^{-1}), running at a distance of 1 meter behind another runner reduced the air resistance by 80%. Drafting is not only beneficial because it reduces the air resistance but also because it reduces the mental effort required to « set and monitor a challenging pace » [53](Polidori et al., 2020).

Polidori et al. (2020) analyzed Kenesia Bekele's performance at the 2019 Berlin marathon where he won in a time of 2 h 01 min and 41 sec. Bekele used a cooperative drafting strategy and adopted three different drafting positions behind three pacers during the race. Using computational fluid dynamics, they estimated a reduction in metabolic power between 1.9 and 2.8% due to drafting. Furthermore, Schickhofer & Hanson (2021) calculated that the reduction in energy cost when drafting in the best drafting formation possible is 3.5%, which corresponds to an increase in velocity of 2.3% and an improvement in time of 154 seconds for a marathon.

4. Recommendations

In this section, we will provide recommendations regarding the transition, swim, bike and run course configurations, the organization of drafting as well as for the location of the event and the climatic conditions that would favor the success of the event.

4.1 Transition zones, swim, cycling and running courses, and strategies to optimize performance

4.1.1 Transition zones

It is necessary to limit the time lost for the transitioning between sports and therefore the transition area needs to be optimally positioned in relation to the swim and cycling finish line. This objective will be reached by limiting the running time from the swim and bike finish line to the transition zone. Intuitively, this can be achieved by having the transition area to be as close as possible to the swim and bike finish. If the ideal running course is close to the swim course then only a single transition area would be needed. Otherwise, a second transition area, distant from the first, may be required if the running course chosen for the *sub7 project* is removed from the swim course.

4.1.2. Swim

The swim needs to be in a calm body of water, because waves reduce the swimming velocity by impacting the swimming efficiency (Kjendlie et al., 2018). Furthermore, swimming in the ocean or in a sea is advantageous because of the added buoyancy due to the salt content in the water (Mclean & Hinrichs, 1998). For instance, the two fastest non-current-assisted swimming times in an IM in 2021 (43 min and 28 sec and 43 min and 53 sec) were achieved at IM Cairns, Australia in a calm ocean, with a wetsuit. Also, as mentioned before, swimming in a wetsuit increases velocity. Since the *sub7 project* would not be eligible as an official world record, a wetsuit could be worn even if the water temperature is higher than 21.9 ℃. However, swimming in warm water in a full wetsuit increases the risk of hyperthermia, so it is not recommended.

4.1.3. Cycling and running

The fastest triathlon cycling times have been achieved on moderately flat courses such as at Challenge Roth, on highways such as at IM Texas and IM Florida and on race car course such as Formula 1 (F1) and Nascar racetracks (Table 5). These courses are optimal to achieve fast bike splits because they are mostly flat. Hence, less energy is wasted to move a bike uphill against the force of gravity, the quality of the road is good, which minimizes rolling resistance, and they have a small number of turns, with potentially the exception of some F1 courses. Regarding this latter point, turns need to be limited such to minimize the amount of kinetic energy lost by breaking or coasting before a turn. Furthermore, turns can be difficult to navigate in a group.

For the current IM world cycling record achieved during the ZTBR, a cycling ramp, similar to a velodrome ramp, was built to allow the triathletes to make a 180º turn without having to slow down. This technology could be used for the *sub7 project* if it were to occur on an out-and-back course such as a highway. However, since the *sub7 project* will most likely occur with the help of pacers it would be important to practice riding the velodrome-like ramp in a group to minimize the risks of crashes during the attempt.

With respect to the run course, it must also be flat and not have any sharp turns, since elevation gain increases the metabolic cost and curves require the runners to generate additional centripetal force on

the ground with their legs, which also increases the metabolic cost (Snyder et al., 2021; Taboga & Kram, 2019).

4.1.4 Meteorological conditions

A significant amount of body heat is produced (Longman et al., 2021) during exercise due to the conversion of chemical energy into mechanical energy, which is a highly inefficient process. The amount of body heat produced is proportional to the exercise intensity. On the other hand, the capacity of the body to dissipate heat to the environment is inversely proportional to the water pressure in the air surrounding the skin and directly proportional to the temperature gradient between the skin and the environment. If too important, body heat gain may lead to premature fatigue and impair performance (Cheuvront et al., 2010). Hence, the choice of the location and the time of the year for the *sub7 project* is crucial; the temperature should neither be too warm nor too cold and the relative humidity should ideally be as low as possible. Solar load also would need to be as low as possible to minimize body heat gain, unless the race is being conducted in relatively cool weather.

Knechtle et al. (2019) analyzed the Boston marathon performances from 1972 to 2018 and observed that for every increase of 1ºC in the average temperature, the winners' finishing times increased by 20 seconds and the average finishing time of all the finishers increased by 1 min 47 seconds. It is well documented that the optimal temperature for a marathon performance is between 10 and 12°C (El Helou et al., 2012; 2007) or between 8 and 15°C (Suping et al., 1992). For instance, the location and the time of day and year for the *INEOS 1:59 challenge* were chosen so that the runners could run at a temperature of about 10°C (INEOS 1:59 challenge, n.d.).

For running performance, the temperature must be low since the effect of convection is minimal due to the relatively slow speed of the runners. However, when cycling, the cooling effect of the wind is significantly more important. Therefore, a temperature of 10 °C may be too cold while cycling, and the « racing » triathlete would need to stop at the first transition to add some clothes and energy may be lost due to thermogenesis. Therefore, a delicate balance between the ideal temperature for cycling and running should be taken into account. However, a possible scenario could be to choose a region where the IM would start after noon when the temperature is in the low 20°C or slightly lower and the radiative effect of the sun is high, so that the « racing » triathlete could begin the marathon at sunset when both the temperature and the solar radiation are declining.

4.1.6 Altitude

For every 305 m increase in altitude, these is an approximate 3% reduction in air density (Levine et al., 2008). Therefore, when cycling at altitude, cyclists encounter less air resistance, which results in an improved performance, unless the physiological detriment associated with the altitude is higher than the improvement associated with the reduction in aerodynamic drag (Atkinson et al., 2003; Bassett, 2000; Capelli & di Prampero, 1995; di Prampero, 2000; Hahn & Gore, 2001; Heil, 2005; Padilla et al., 2000). For instance, both the hour record and the 4000 m cycling records were achieved at the Aguascalientes velodrome in Mexico, which is at an altitude of 1800 m (Delaney, B., 2021; UCI, 2021).

It would therefore be tempting for organizers to consider having the *sub7* project at altitude. However, altitude is associated with a decrease in performance for aerobic activities due to a decrease in $\dot{V}O_{2max}$ and an increase in the relative intensity at any speed or power output (Burtscher et al., 2018; Garvican-Lewis et al., 2014; 2015). Furthermore, since the effect of air resistance while running a marathon is

low, the reduction in air density whilst running at altitude is not beneficial since the physiological impairment is considerable.

4.2.4 Time of year and location

As previously mentioned, the bike and run courses must be flat, the swim must be in a calm body of water and ideally in salt water and the temperature and humidity must be low, but manageable on the bike without the addition of clothing. One ideal location would be Bahrain, which is where the half-IM world record was broken. The swim would occur at the Bahrain bay which is a calm body of salt water. The bike and run courses would be flat and have a small number of turns. The ideal time of year would be January; it is the coldest month of the year in Bahrain with average temperature ranging between 14.7 and 20ºC, the water temperature is about 19.8ºC (Weather-Atlas, n.d.), rain is sporadic, solar radiation is significantly lower in January (4.8 kWh/m^2 day compared to over 6.5 kWh/m^2 day in the summer months) (Alnaser et al., 2014) and sunset occurs at about 5 PM. Therefore, the IM could begin at 13h00 so to have the run start when both the temperature and solar radiation are lower.

4.3 Organization of drafting

The way drafting will be structured for each of the three sports must be carefully planned and orchestrated for it to provide the best results possible. For the swim, there are two possible positions where a swimmer can be situated to benefit from the draft of other swimmers. One option is to swim between 0 to 50 cm behind the toes of the lead swimmers. The other position, called lateral drafting, requires the swimmer to be located 50 to 100 cm back from the hands of the lead swimmer. However, swimming at the feet is more advantageous (Chatard & Wilson, 2003). In order to maximize the reduction of hydrodynamic drag, the « racing » triathlete should swim behind five pacers positioned in an arrowhead position (Figure 2a).

For the cycling, based on Blocken et al. (2018)'s study, the optimal situation would be to have 6 lead cyclists in front of the "racing" triathlete and to try to maintain a space of 5 cm to 15 cm between each cyclist (Figure 2b). The utilization of radio communication is recommended so that the race organizers and coaches can communicate with the lead cyclists and the « racing » triathlete. The 6 lead cyclists would need to rotate in order to share the lead and therefore spend short period of times at the front where the aerodynamic drag is the greatest (Shirasaki et al., 2017). They could be replaced by other cyclists at the half point of the 180 km to make sure that the « racing » triathlete has 6 fresh lead cyclists throughout the entire cycling distance.

Motorcycles could be used to provide on-course food and fluid to the triathletes. As a result, instead of having to slow down and get out of his aerodynamic position on his bicycle to grab bottles or gels from an aid station, the « racing » triathlete would be able to maintain his aerodynamic position and speed, which would allow him to save time and energy. The feeding for the pacers should occur as the lead pacer finishes his pull at the front of the group so that he can coast at the end of the group and receive food and fluids without putting the other cyclists at risk.

For the run, a drafting organization similar to the one used for the sub 2-h marathon attempts is recommended (Figure 2c). For the first sub 2-h marathon attempt, it was decided to have new pacers after every lap of 2.4 km. Kipchoge was running behind another runner who was preceded by 6 runners who were forming an arrowhead. For the second attempt at breaking the 2-h mark, 7 pacers were used, but this time 5 pacers were running in front of Kipchoge in an inverted arrow-head formation and 2 pacers were running behind him (Polidori et al., 2020). For the *sub7 project*, 7 pacers should be used, and in order to make sure that they can sustain that pace, 7 new pacers would replace them at the half-

marathon mark. People riding electric bicycles could ride alongside the runners to provide food, liquids and verbal encouragement.

5. Discussion

We determined, based on the trends of the improvement of the IM times over the years, that a sub 7-h IM is unlikely to be achieved without any external assistance. However, this prediction is based solely on trends, so it is not impossible that a sub 7-h IM without any external assistance could be achieved in the future thanks to sophisticated training programs and better monitoring of the recovery process. The arrival of new technologies could also be a game changer. For instance, the use of 3D printing in the development of time trial handlebars with the goal of improving aerodynamism could be extended to create custom, wind-cheating bicycles (Croxton, 2021). Although a taboo topic, it cannot be ruled out that performance-enhancing drugs could be used without being detected, either because of micro-dosing strategies or because the active compound has not been yet been identified by researchers (Joyner et al., 2020). Furthermore, over the past few years, triathletes have begun to compete in IM races at an earlier age which may provide them with more time to improve at that distance while there are still at their peak fitness level.

In this article, courses with a significant negative elevation and with a current-assisted swim were not considered because they fell outside our definition of external assistance. However, a current-assisted swim could help reduce the overall time by as much as 8 minutes[7]. Also, a sub 7-h IM could possibly be achieved by swimming in a lake at altitude and then immediately cycling down to a town at low altitude, where the racing athletes would complete their cycling ride. The descent to a lower altitude would allow triathletes to save precious time and energy and enable them to start the run on a fresher body and mind.

The *sub7 project*, similarly to the *sub2* marathon projects, would require a lot of organization, planning and substantial funding. Furthermore, it would also require a strong commitment in time from the organizers, the pacers and the « racing » triathlete involved in this event. The triathlete must fully commit to this event, so it should not occur during an Olympic year. Furthermore, he would need to train specifically for this event for many months and to practice the pacing and drafting strategies with the pacers to optimize efficiency and reduce the risks of crashes, especially while cycling. Finally, this achievement would need to be executed, of course, in an ideal location and, most importantly, under perfect meteorological conditions. Therefore, it is recommended to not have the race planned on a fixed day, but rather to plan the race to occur within a spectrum of days ranging from 3 to 5, for instance. Therefore, a careful coordination between race organizers and local authorities and planning of training, diet and hydration for the « racing » triathlete in the days leading to the race, and within the targeted possible racing days, if need be, would be required.

In conclusion, a sub 7-h IM would be a significant sporting achievement similar to the first sub 4 min mile and the first sub 2-h marathon and physical, psychological and technological boundaries would need to be broken.

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[7] This reduction in time is estimated by comparing the current-assisted swim time to non-current-assisted swim times.

Références

Alnaser, W. E., Alnaser, N. W., & Batarseh, I. (2014). Bahrain's BAPCO 5MWp PV Grid–Connected Solar Project. *International Journal of Power and Renewable Energy Systems*, 1(14), 72-84.

Atkinson, G., Davison, R., Jeukendrup, A., & Passfield, L. (2003). Science and cycling : Current knowledge and future directions for research. *Journal of Sports Sciences*, *21*(9), 767-787. https://doi.org/10.1080/0264041031000102097

Barry, N., Burton, D., Sheridan, J., Thompson, M., & Brown, N. A. (2015a). Aerodynamic performance and riding posture in road cycling and triathlon. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*, *229*(1), 28-38. https://doi.org/10.1177/1754337114549876

Barry, N., Burton, D., Sheridan, J., Thompson, M., & Brown, N. A. T. (2015b). Aerodynamic drag interactions between cyclists in a team pursuit. *Sports Engineering*, *18*(2), 93-103. https://doi.org/10.1007/s12283-015-0172-8

Bassett, D. R. (2000). Limiting factors for maximum oxygen uptake and determinants of endurance performance: *Medicine & Science in Sports & Exercise*, 70. https://doi.org/10.1097/00005768-200001000-00012

Bentley, D. J., Libicz, S., Jougla, A., Coste, O., Manetta, J., Chamari, K., & Millet, G. P. (2007). The effects of exercise intensity or drafting during swimming on subsequent cycling performance in triathletes. *Journal of Science and Medicine in Sport*, *10*(4), 234-243. https://doi.org/10.1016/j.jsams.2006.05.004

Blocken, B., Defraeye, T., Koninckx, E., Carmeliet, J., & Hespel, P. (2013). CFD simulations of the aerodynamic drag of two drafting cyclists. *Computers & Fluids*, *71*, 435-445. https://doi.org/10.1016/j.compfluid.2012.11.012

Brisswalter, J., & Hausswirth, C. (2008). Consequences of Drafting on Human Locomotion : Benefits on Sports Performance. *International Journal of Sports Physiology and Performance*, *3*(1), 3-15. https://doi.org/10.1123/ijspp.3.1.3

Burtscher, M., Niedermeier, M., Burtscher, J., Pesta, D., Suchy, J., & Strasser, B. (2018). Preparation for Endurance Competitions at Altitude : Physiological, Psychological, Dietary and Coaching Aspects. A Narrative Review. *Frontiers in Physiology*, *9*, 1504. https://doi.org/10.3389/fphys.2018.01504

Capelli, C., & di Prampero, P. E. (1995). Effects of altitude on top speeds during 1 h unaccompanied cycling. *European Journal of Applied Physiology and Occupational Physiology*, *71*(5), 469-471. https://doi.org/10.1007/BF00635883

Chatard, J.-C., & Wilson, B. (2003). Drafting Distance in Swimming: *Medicine & Science in Sports & Exercise*, *35*(7), 1176-1181. https://doi.org/10.1249/01.MSS.0000074564.06106.1F

Cheuvront, S. N., Kenefick, R. W., Montain, S. J., & Sawka, M. N. (2010). Mechanisms of aerobic performance impairment with heat stress and dehydration. *Journal of Applied Physiology*, *109*(6),

1989-1995. https://doi.org/10.1152/japplphysiol.00367.2010

Crouch, T. N., Burton, D., LaBry, Z. A., & Blair, K. B. (2017). Riding against the wind : A review of competition cycling aerodynamics. *Sports Engineering*, *20*(2), 81-110. https://doi.org/10.1007/s12283-017-0234-1

Delextrat, A., Tricot, V., Bernard, T., Vercruyssen, F., Hausswirth, C., & Brisswalter, J. (2003). Drafting during Swimming Improves Efficiency during Subsequent Cycling: *Medicine & Science in Sports & Exercise*, *35*(9), 1612-1619. https://doi.org/10.1249/01.MSS.0000084422.49491.2C

de Lucas, R. D., Balikian, P., Neiva, C. M., Greco, C. C., & Denadai, B. S. (2000). The effects of wet suits on physiological and biomechanical indices during swimming. *Journal of Science and Medicine in Sport*, *3*(1), 1-8. https://doi.org/10.1016/S1440-2440(00)80042-0

Delaney, B. (2021, August 18). *Ashton Lambie demolishes 4km IP world record with a time of 3:59:92*. VeloNews. https://www.velonews.com/news/ashton-lambie-demolishes-ip-world-record-with-an-unofficial-359-92/

Denison, J. (2006). Inhibiting Progress : The Record of the Four-Minute Mile. *Sport in History*, *26*(2), 280-288. https://doi.org/10.1080/17460260600786930

di Prampero, P. E. (2000). Cycling on Earth, in space, on the Moon. *European Journal of Applied Physiology*, *82*(5-6), 345-360. https://doi.org/10.1007/s004210000220

El Helou, N., Tafflet, M., Berthelot, G., Tolaini, J., Marc, A., Guillaume, M., Hausswirth, C., & Toussaint, J.-F. (2012). Impact of Environmental Parameters on Marathon Running Performance. *PLoS ONE*, *7*(5), e37407. https://doi.org/10.1371/journal.pone.0037407

Ely, M. R., Cheuvront, S. N., Roberts, W. O., & Montain, S. J. (2007). Impact of Weather on Marathon-Running Performance. *Medicine & Science in Sports & Exercise*, *39*(3), 487-493. https://doi.org/10.1249/mss.0b013e31802d3aba

Faria, E. W., Parker, D. L., & Faria, I. E. (2005). The Science of Cycling : Factors Affecting Performance ??? Part 2. *Sports Medicine*, *35*(4), 313-337. https://doi.org/10.2165/00007256-200535040-00003

Foster, C., de Koning, J., Bischel, S., Casolino, E., Malterer, K., O'Brien, K., Rodríguez-Marroyo, J., Splinter, A., Thiel, C., Van Tunen, J. (2012). Pacing strategies for endurance performance. In I. Mujika (Ed.), Endurance training – Science and practice (pp. 85–98). Vitoria-Gasteiz: Self-published.

García-López, J., Rodríguez-Marroyo, J. A., Juneau, C.-E., Peleteiro, J., Martínez, A. C., & Villa, J. G. (2008). Reference values and improvement of aerodynamic drag in professional cyclists. *Journal of Sports Sciences*, *26*(3), 277-286. https://doi.org/10.1080/02640410701501697

Garvican-Lewis, L. A., Clark, B., Martin, D. T., Schumacher, Y. O., McDonald, W., Stephens, B., Ma, F., Thompson, K. G., Gore, C. J., & Menaspà, P. (2015). Impact of Altitude on Power Output during Cycling Stage Racing. *PLOS ONE*, *10*(12), e0143028. https://doi.org/10.1371/journal.pone.0143028

Garvican-Lewis, L. A., Schumacher, Y. O., Clark, S. A., Christian, R., Menaspà, P., Plowman, J.,

Stephens, B., Qi, J., Fan, R., He, Y., Martin, D. T., Thompson, K. G., Gore, C. J., & Ma, F. (2014). Stage racing at altitude induces hemodilution despite an increase in hemoglobin mass. *Journal of Applied Physiology*, *117*(5), 463-472. https://doi.org/10.1152/japplphysiol.00242.2014

Gay, A., López-Contreras, G., Fernandes, R. J., & Arellano, R. (2020). Is Swimmers' Performance Influenced by Wetsuit Use? *International Journal of Sports Physiology and Performance*, *15*(1), 46-51. https://doi.org/10.1123/ijspp.2018-0891

Grappe, F., Candau, R., Barbier, B., Hoffman, M. D., Belli, A., & Rouillon, J.-D. (1999). Influence of tyre pressure and vertical load on coefficient of rolling resistance and simulated cycling performance. *Ergonomics*, *42*(10), 1361-1371. https://doi.org/10.1080/001401399185009

Grappe, F., Candau, R., Belli, A., & Rouillon, J. D. (1997). Aerodynamic drag in field cycling with special reference to the Obree's position. *Ergonomics*, *40*(12), 1299-1311. https://doi.org/10.1080/001401397187388

Griffith, M. D., Crouch, T., Thompson, M. C., Burton, D., Sheridan, J., & Brown, N. A. T. (2014). Computational Fluid Dynamics Study of the Effect of Leg Position on Cyclist Aerodynamic Drag. *Journal of Fluids Engineering*, *136*(10), 101105. https://doi.org/10.1115/1.4027428

Hahn, A. G., & Gore, C. J. (2001). The Effect of Altitude on Cycling Performance : A Challenge to Traditional Concepts. *Sports Medicine*, *31*(7), 533-557. https://doi.org/10.2165/00007256-200131070-00008

Hausswirth, C., Bigard, A. X., Guezennec, C. Y. (1997). Relationships between running mechanics and energy cost of running at the end of a triathlon and a marathon. *International Journal of Sports Medicine*, 18 (5): 330-339.

Hausswirth, C., & Brisswalter, J. (2008). Strategies for Improving Performance in Long Duration Events : Olympic Distance Triathlon. *Sports Medicine*, *38*(11), 881-891. https://doi.org/10.2165/00007256-200838110-00001

Hausswirth, C., Vallier, J.-M., Lehenaff, D., Brisswalter, J., Smith, D., Millet, G., & Dreano, P. (2001). Effect of two drafting modalities in cycling on running performance: *Medicine and Science in Sports and Exercise*, *33*(3), 485-492. https://doi.org/10.1097/00005768-200103000-00023

Heil, D. P. (2005). Body size as a determinant of the 1-h cycling record at sea level and altitude. *European Journal of Applied Physiology*, *93*(5-6), 547-554. https://doi.org/10.1007/s00421-004-1256-5

Hoogkamer, W., Kram, R., & Arellano, C. J. (2017). How Biomechanical Improvements in Running Economy Could Break the 2-hour Marathon Barrier. *Sports Medicine*, *47*(9), 1739-1750. https://doi.org/10.1007/s40279-017-0708-0

INEOS 1:59 Challenge. (n.d.) *Why Vienne proved to be the outstanding candidate to host the Ineos 1:59 challenge.* INEOS 1:59 Challenge. https://www.ineos159challenge.com/news/why-vienna-proved-to-be-the-outstanding-candidate-to-host-the-ineos-1-59-challenge/

Jeukendrup, A. E., & Martin, J. (2001). Improving Cycling Performance : How Should We Spend Our Time and Money. *Sports Medicine*, *31*(7), 559-569. https://doi.org/10.2165/00007256-

200131070-00009

Joyner, M. J., Ruiz, J. R., & Lucia, A. (2011). The two-hour marathon : Who and when? *Journal of Applied Physiology*, *110*(1), 275-277. https://doi.org/10.1152/japplphysiol.00563.2010

Kjendlie, P.-L., Pedersen, T., & Stallman, R. (2018). The Effect of Waves on the Performance of Five Different Swimming Strokes. *The Open Sports Sciences Journal*, *11*(1), 41-49. https://doi.org/10.2174/1875399X01811010041

Knechtle, B., Di Gangi, S., Rüst, C. A., Villiger, E., Rosemann, T., & Nikolaidis, P. T. (2019). The role of weather conditions on running performance in the Boston Marathon from 1972 to 2018. *PLOS ONE*, *14*(3), e0212797. https://doi.org/10.1371/journal.pone.0212797

Lacour, J.-R., & Bourdin, M. (2015). Factors affecting the energy cost of level running at submaximal speed. *European Journal of Applied Physiology*, *115*(4), 651-673. https://doi.org/10.1007/s00421-015-3115-y

Larsen, H. B. (2003). Kenyan dominance in distance running. *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology*, *136*(1), 161-170. https://doi.org/10.1016/S1095-6433(03)00227-7

Lepers, R. (2008). Analysis of Hawaii Ironman Performances in Elite Triathletes from 1981 to 2007. *Medicine & Science in Sports & Exercise*, *40*(10), 1828-1834. https://doi.org/10.1249/MSS.0b013e31817e91a4

Longman, D. P., Murray, A., Roberts, R., Oakley, S., Wells, J. C. K., & Stock, J. T. (2021). Energetics as a driver of human morphological thermal adaptation; evidence from female ultra-endurance athletes. *Evolutionary Human Sciences*, *3*, e22. https://doi.org/10.1017/ehs.2021.17

Lucia, A., Esteve-Lanao, J., Oliván, J., Gómez-Gallego, F., San Juan, A. F., Santiago, C., Pérez, M., Chamorro-Viña, C., & Foster, C. (2006). Physiological characteristics of the best Eritrean runners—Exceptional running economy. *Applied Physiology, Nutrition, and Metabolism*, *31*(5), 530-540. https://doi.org/10.1139/h06-029

Lukes, R. A., Chin, S. B., & Haake, S. J. (2005). The understanding and development of cycling aerodynamics. *Sports Engineering*, *8*(2), 59-74. https://doi.org/10.1007/BF02844004

Martin, J. C., Milliken, D. L., Cobb, J. E., McFadden, K. L., & Coggan, A. R. (1998). Validation of a Mathematical Model for Road Cycling Power. *Journal of Applied Biomechanics*, *14*(3), 276-291. https://doi.org/10.1123/jab.14.3.276

Padilla, S., Mujika, I., Orba??Anos, J., & Angulo, F. (2000). Exercise intensity during competition time trials in professional road cycling: *Medicine & Science in Sports & Exercise*, *32*(4), 850-856. https://doi.org/10.1097/00005768-200004000-00019

Peeling, P., & Landers, G. (2009). Swimming intensity during triathlon : A review of current research and strategies to enhance race performance. *Journal of Sports Sciences*, *27*(10), 1079-1085. https://doi.org/10.1080/02640410903081878

Santos-Concejero, J., Oliván, J., Maté-Muñoz, J. L., Muniesa, C., Montil, M., Tucker, R., & Lucia,

A. (2015). Gait-Cycle Characteristics and Running Economy in Elite Eritrean and European Runners. *International Journal of Sports Physiology and Performance*, *10*(3), 381-387. https://doi.org/10.1123/ijspp.2014-0179

Saunders, P. U., Telford, R. D., Pyne, D. B., Cunningham, R. B., Gore, C. J., Hahn, A. G., & Hawley, J. A. (2004). Improved running economy in elite runners after 20 days of simulated moderate-altitude exposure. *Journal of Applied Physiology*, *96*(3), 931-937. https://doi.org/10.1152/japplphysiol.00725.2003

Sousa, C., Barbosa, L., Sales, M., Santos, P., Tiozzo, E., Simões, H., Nikolaidis, P., & Knechtle, B. (2019). Cycling as the Best Sub-8-Hour Performance Predictor in Full Distance Triathlon. *Sports*, *7*(1), 24. https://doi.org/10.3390/sports7010024

Schickhofer, L., Hanson, H. (2021). Aerodynamic effects and performance improvements of running in drafting formations. *Journal of Biomechanics,* 122 (2021) 110457. doi:10.1016/j.jbiomech.2021.110457.

Suping, Z., Guanglin, M., Yanwen, W., & Ji, L. (1992). Study of the relationships between weather conditions and the marathon race, and of meteorotropic effects on distance runners. *International Journal of Biometeorology*, *36*(2), 63-68. https://doi.org/10.1007/BF01208915

Tomikawa, M., Shimoyama, Y., & Nomura, T. (2008). Factors related to the advantageous effects of wearing a wetsuit during swimming at different submaximal velocity in triathletes. *Journal of Science and Medicine in Sport*, *11*(4), 417-423. https://doi.org/10.1016/j.jsams.2007.02.005

Trirating. (2022, Januray 4). *Ironman-Distance Records*. Trirating. https://www.trirating.com/ironman-distance-records/

Trirating. (n.d.) *Trying to predict Ironman times from 70.3 ratings.* Trirating. https://www.trirating.com/trying-to-predict-ironman-times-from-70-3-ratings/

UCI. (2021, October 10). *Alex Dowsett makes new attempt on UCI Hour Record timed by Tissot*. UCI. https://www.uci.org/pressrelease/alex-dowsett-makes-new-attempt-on-uci-hour-record-timed-by-tissot/6nA5r4yxTlJp9yVM9c67Nj

Weather-Atlas. (n.d). January weather forecast and climate in Manama, Bahrain. https://www.weather-atlas.com/en/bahrain/manama-weather-january#climate_text_1

Zamparo, P., Bonifazi, M., Faina, M., Milan, A., Sardella, F., Schena, F., & Capelli, C. (2005). Energy cost of swimming of elite long-distance swimmers. *European Journal of Applied Physiology*, *94*(5-6), 697-704. https://doi.org/10.1007/s00421-005-1337-0

Zingg, M. A., Rüst, C. A., Rosemann, T., Lepers, R., & Knechtle, B. (2014). Analysis of swimming performance in FINA World Cup long-distance open water races. *Extreme Physiology & Medicine*, *3*(1), 2. https://doi.org/10.1186/2046-7648-3-2

Tables

Table 1

Table 1. World record Ironman^{TM} triathlon performances.

Year	Athletes	Total time (h:min:sec)
1989	Dave Scott	8: 01: 32
1996	Lothar Leder	7: 57: 02
1997	Luc Van Lierde	7: 50: 27
2011	Marino Vanhoenacker	7: 45: 58
2011	Andreas Raelert	7: 41: 33
2016	Jan Frodeno	7: 35: 39
2021	Jan Frodeno	7 :27 :53
2021	Kristian Blummenfelt	7 :21 :42*

* For the purpose of this article, the time of 7 h 21 min and 42 sec achieved by Kristian Blummenfelt is not considered the world record since the swim was current-assisted.

Table 2

Table 2. Evolution of the racing time of the winners of the Challenge Roth IM triathlon from 1990 to 2019.

Years 1990-1999	Total time (h:min:sec)	Years 2000-2009	Total time (h:min:sec)	Years 2010-2019	Total time (h:min:sec)
1990	8:21:13	2000	8:19:38	2010	7:52:36
1991	8:04:54	2001	8:10:39	2011	7:41:33
1992	8:06:12	2002	8:17:25	2012	7:59:59
1993	8:03:19	2003	8:11:50	2013	7:52:01
1994	8:01:59	2004	7:57:50	2014	7:56:00
1995	8:08:07	2005	7:58:45	2015	7:51:28
1996	7:57:02	2006	8:00:52	2016	7:35:39
1997	7:50:24	2007	7:58:45	2017	7:59:07
1998	8:03:59	2008	8:09:34	2018	7:46:23
1999	7:56:00	2009	7:55:53	2019	7:59:02

Table 3.

Table 3. Comparison of the fastest half-IM and IM triathlons of some of the best current long-distance triathletes in the world.

Athletes	Half-IM best times (h:min:sec)	Doubling of the Half-IM best times (h:min:sec)*	IM best times (h:min:sec)	Difference (%)†
Andreas Dreitz	3:40:12	7:16:54	7:53:06	7.7
Bart Aernouts	3:44:38	7:25:46	7:55:12	6.2
Braden Currie	3:23:33	6:43:36	7:54:58	15
Daneil Baekkegard	3:29:18	6:55:06	7:52:58	12.2
Denis Chevrot	3:41:14	7:18:58	7:51:00	6.8
Florian Angert	3:41:27	7:19:24	7:45:05	5.5
Gustav Iden	3:29:25	6:55:20	7:42:56	10.3
Jackson Laundry	3:39:50	7:16:10	8:26:00	13.8
Jan Frodeno	3:36:31	7:09:32	7:27:53	4.1
Jan Van Berkel	3:40:49	7:18:08	7:39:40	4.7
Joe Skipper	3:55:32	7:47:34	7:53:52	1.3
Kristian Hogenhaug	3:50:37	7:37:44	7:37:46	0
Kyle Smith	3:39:43	7:15:56	8:08:53	10.8
Leon Chevalier	3:50:20	7:37:10	7:57:02	4.2
Lionel Sanders	3:38:18	7:13:06	7:43:30	6.6
Matt Hanson	3:46:48	7:30:06	7:39:25	2
Patrick Lange	3:43:46	7:24:02	7:45:21	4.6
R. Svenningsson	3:29:18	6:55:06	7:51:33	12
Sam Appleton	3:43:58	7:24:26	8:09:54	9.3
Sam Long	3:37:34	7:11:38	7:55:33	9.2
Average	**3:40:09**	**7:16:47**	**7:51:35**	**7.3 ± 4.2**

*Half-IM time x 2, substracting a time of 3 min and 30 sec for the transition times.

†IM best time - doubling of the half-IM best time

Table 4.

Table 4. Time for each discipline of the winners of the Challenge Roth triathlon from 1990 to 2019 in relation to total racing time.

Years	Total time (h:min:sec)	Swim (h:min:sec)	% Swim	Cycle (h:min:sec)	% Cycle	Run (h:min:sec)	% Run
1990	8:21:13	0:49:14	9.82	4:43:30	56.56	2:48:29	33.61
1991	8:04:54	0:49:38	10.24	4:30:26	55.77	2:44:50	33.99
1992	8:06:12	0:50:52	10.46	4:29:38	55.46	2:45:24	34.02
1993	8:03:19	0:53:23	11.04	4:21:04	54.02	2:48:51	34.94
1994	8:01:59	0:49:41	10.31	4:23:53	54.75	2:48:25	34.94
1995	8:08:07	0:51:11	10.49	4:20:28	53.36	2:56:28	36.15
1996	7:57:02	0:49:33	10.39	4:24:06	55.36	2:43:23	34.25
1997	7:50:24	0:44:51	9.53	4:28:47	57.14	2:36:49	33.34
1998	8:03:59	0:48:16	9.97	4:23:02	54.35	2:52:41	35.68
1999	7:56:00	0:50:59	10.71	4:15:47	53.74	2:49:13	35.55
2000	8:19:38	0:47:43	9.55	4:31:18	54.3	3:00:37	36.15
2001	8:10:39	0:46:51	9.55	4:33:09	55.67	2:50:37	34.77
2002	8:17:25	0:50:50	10.22	4:32:09	54.71	2:54:26	35.07
2003	8:11:50	0:50:42	10.31	4:28:57	54.68	2:52:08	35
2004	7:57:50	0:47:59	10.04	4:28:27	56.18	2:41:22	33.77
2005	7:58:45	0:47:33	9.93	4:24:32	55.25	2:46:38	34.81
2006	8:00:52	0:46:53	9.75	4:27:51	55.7	2:46:06	34.54
2007	7:58:45	0:49:45	10.39	4:17:58	53.89	2:46:39	34.81
2008	8:09:34	0:48:47	9.96	4:31:59	55.55	2:48:49	34.48
2009	7:55:53	0:50:30	10.61	4:22:56	55.25	2:42:30	34.15
2010	7:52:36	0:46:51	9.91	4:24:48	56.03	2:40:53	34.04
2011	7:41:33	0:46:18	10.03	4:13:11	54.85	2:42:06	35.12
2012	7:59:59	0:47:41	9.93	4:31:07	56.49	2:41:13	33.59
2013	7:52:01	0:46:05	9.76	4:16:24	54.32	2:49:35	35.93
2014	7:56:00	0:48:58	10.29	4:21:23	54.91	2:45:40	34.8
2015	7:51:28	0:47:33	10.09	4:10:55	53.22	2:53:02	36.7
2016	7:35:39	0:45:22	9.96	4:09:25	54.74	2:40:36	35.25
2017	7:59:07	0:52:55	11.05	4:20:42	54.41	2:45:28	34.54
2018	7:46:23	0:47:59	10.29	4:09:30	53.5	2:48:57	36.23
2019	7:59:02	0:51:28	10.74	4:14:59	53.23	2:52:38	36.04
Average (%)			**10.2±0.4**		**54.9±1.0**		**34.9±0.9**

Table 5.

Table 5. Fastest cycling times in an IM since 2005.

Year	Athletes	Event	Type of bike course	Time (h:min:sec)
2005	Torbjorn Sindballe	IM World Championships Hawaï	Flat roads with rolling hills	4:21:36
2006	Mitchell Anderson	IM Western Australia	Flat roads	4:18:07
2007	Thomas Hellriegel	Challenge Roth	Flat roads with rolling hills	4:16:18
2009	Normann Stadler	Challenge Roth	Flat roads with rolling hills	4:14:42
2010	Sebastian Kienle	Challenge Roth	Flat roads with rolling hills	4:14:07
2011	Andreas Raelert	Challenge Roth	Flat roads with rolling hills	4:11:43
2012	Andrew Starykowicz	IM Florida	Flat highway	4:04:39
2013	Andrew Starykowicz	IM Florida	Flat highway	4:02:17
2017	Andrew Starykowicz	IM Texas	Flat highway	4:01:14
2021	Jan Frodeno	Zwift Tri Battle Royale	Flat roads	3:55:22

Table 6.

Table 6. Modulation of the cycling time and power output based on different drag coefficient scenarios and on different power reduction from drafting.

Variables	Scenario 1	Scenario 2
Cyclist weight (kg)	74	74
Equipment (bicycle, wheels, etc.) weight (kg)	8	8
Total weight (kg)	82	82
Frontal Area (m^2)	0.3	0.32
Drag coefficient (dimensionless)	0.7	0.7
Drag coefficient x frontal area (CdA)	0.21	0.224
Air density (Rho) (kg/m^3)	1.226	1.226
Rolling resistance (dimensionless)	0.004	0.004
Slope G (%)	0	0
Cycling time (h:min:sec)	**Power output (W)**	
4:00:00	292	308
3:55:00	309	327
3:50:00	328	347
3:49:32	330	349
3:49:32 with drafting (assuming 35 % power reduction)	214	227
3:49:32 with drafting (assuming 40 % power reduction)	198	209

Figure legends

Figure 1. a) Prediction of the best IM finishing time from the best times achieved over the distance from 1989 to 2021. **b)** Prediction of the best IM finishing time from the best times achieved each year over the distance during IM Challenge Roth from 1990 to 2019. SEE: standard error of the estimate.

Figure 2. Recommended drafting organizations for **a)** swimming, **b)** cycling and **c)** running.
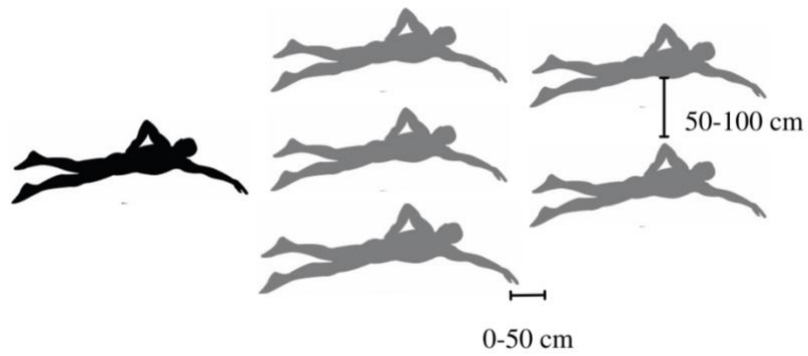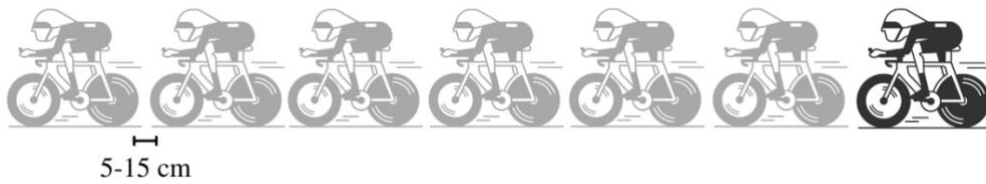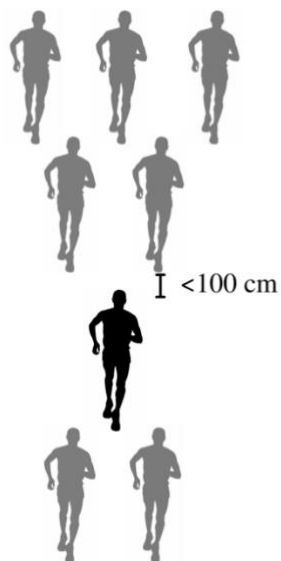
Figure 1

Figure 2

A

50-100 cm

0-50 cm

B

5-15 cm

C

<100 cm
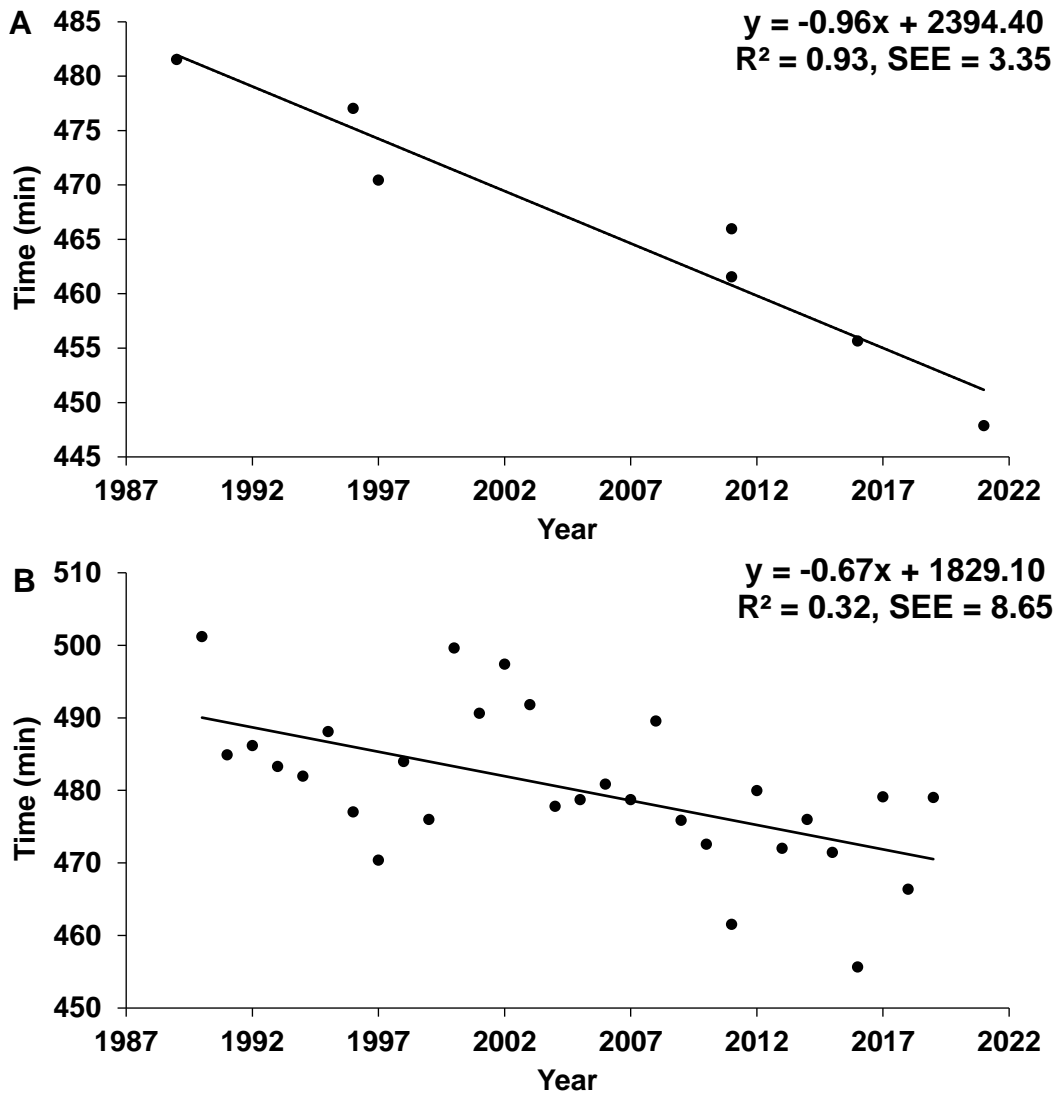
1.   Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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