INTRODUCTION:

Triathlon is a sport with rapidly growing popularity. According to statista.com (2019), the number of participants increased by 3.12 million between 2006 and 2017, which corresponds to a growth of 439%. In 2015, the triathlon event organizer “Challenge” commissioned a market analysis. The results are clear: An average triathlete has a college degree, earns $100-150,000 annually and is willing to spend $4,000-5,000 of it on his sport. In addition to training devices, entry fees and sports nutrition, these investments also include racing equipment. An important part of this is the race suit which is the only one used during all three disciplines of triathlon. The high willingness to spend money ensures that the development of new technologies, including the field of race clothing not only in the professional sector, but also in the amateur sector is constantly driven forward. And the area of research is large: competition clothing must optimize performance in two different media (water and air) and at different speeds. It must fit tightly but must not restrict freedom of movement. It must provide adequate thermoregulation and must not tear on contact. In this review the basic requirements of the respective discipline to the garment, as well as the technical possibilities and a corresponding classification into the rules of the International Triathlon Union (ITU) shall be presented.

SWIMMING:

REGULATIONS:

Swimming during a triathlon can be very different from competition to competition. The event can take place in a swimming pool with lanes or in open water (lake or sea) and the standard distances vary from 750m (sprint distance) to 3800m (long distance). The key factor in the swimming regulations is the permission, obligation or prohibition to use wetsuits. Depending on the athlete's racing category, water temperature and distance to swim, triathletes might not be allowed to compete with neoprene garment (Tab. 1 and Tab. 2).

Swim Length	Forbidden	Mandatory*
Up to 1500m	20°C and above	15.9°C and below
1501m and longer	22°C and above	15.9°C and below

Table 1. Wetsuit regulations for elite, U23, Junior and youth athletes. *When mandatory, the wetsuit must cover at least the torso (ITU, 2018).

Swim Length	Forbidden	Mandatory*
Up to 1500m	22°C and above	15.9°C and below
1501m and longer	24.6°C and above	15.9°C and below

Table 2. Wetsuit regulations for age group athletes. * When mandatory, the wetsuit must cover at least the torso (ITU, 2018)

For the non-wetsuit swims, the athletes must wear approved triathlon suits. These have to be 100% textile material and are neither allowed to cover any part of the arms below the elbow nor any part of the legs below the knees (ITU, 2018).

TECHNICAL POSSIBILITIES:

If the additional usage of wetsuits in the swimming section is prohibited, the material and the design of the race suit is crucial. The most important characteristic of the triathlon suit should be that it allows the athlete to compete within the shortest possible time. And this is a three-folded property: Firstly, the drag in the water should be reduced as much as possible to minimize the energy requirement for swimming at the high speeds. Referring to basic fluid mechanics this can be achieved by 1) reducing the wetted area; 2) increasing laminar flow around the body and therefore reducing turbulent flow; 3) reduce flow separation by promoting attached flow and 4) reducing the production of waves and spray (Wilcox, 2000). Drag reducing swim-suits are able to cut down the overall drag by 10-15% (Walsh, 1998) whereas shaving body hair of an athlete reduces the overall drag only by 9% (Starling et al., 1995). This can be achieved by the right choice of material including a low drag coefficient, a tight fit to reduce the wetted area and by placing protuberances (vortex generators) at strategic places of the swimmer such as the buttocks (Mollendorf et al., 2004). Mollendorf and colleagues (2004) also found out that swim-suits covering only body parts below the waist do not have any or at least no significant effect on the drag reduction. From their data it can also be derived that coverage of the leg below the knee does not have an influence on the overall water resistance during swimming.

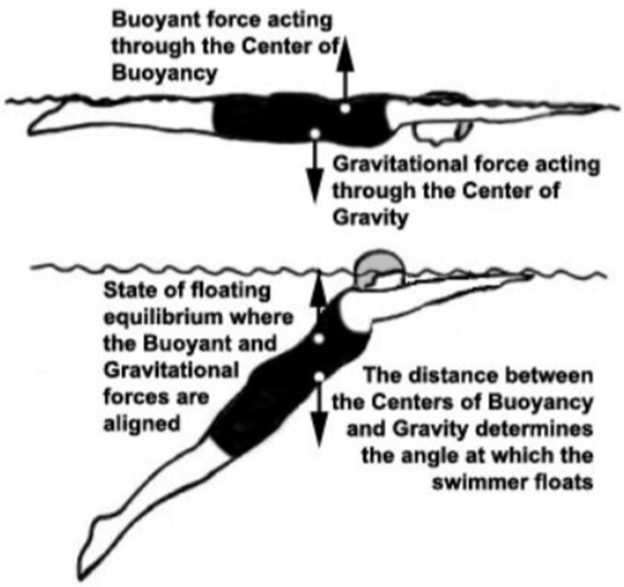

Figure 1. The roles of the centres of buoyancy and gravity and how they determine (Rushell, 2007).

Secondly, the energy requirement at all speeds in swimming is also dependent on the interaction of the individual body density of the athlete, the distribution of the various densities inside the body and the density of the surrounding medium (saltwater, fresh water or also impurities of the water, which is why the location of the competition plays a role in swimming mechanics). If a body is floating in the water, two forces are acting upon it: the gravitational force and the buoyant force which is exerted by the water. The center of gravity and the center of buoyancy usually are not in the same spot which causes a rotation of the body while swimming and therefore increases the energy requirement during a race because the athlete needs to counteract this moment actively (Figure 1). The Buoyant force and its center of application are dependent upon the interaction of densities mentioned above. Lower densities of the body and higher densities of the surrounding water increase the buoyant force and vice versa. The divergence between the locations of the centres is in females for example much smaller (e.g. because of higher fat content in the legs and lower lung volume) and therefore it is easier for them to swim with a more favorable water position (Rushell, 2007). But the buoyant force cannot only be influenced by the body composition of the athlete but also by the technology of the swim suit. By trapping air inside the suit at positions more distal than the center of gravity, the center of buoyancy can be changed to almost coincide with the center of gravity. In swimming standalone competitions, this is prohibited by the following lines in the FINA Requirements for Swimwear Approval (FRSA, 2017): “[…] any material added on to the surface of the textile fabric (any part thereof) or processing of the same […] shall not close the overall open mesh structure of the base textile fabric […]”. Such a prohibition does not exist in the ITU competition rules which leads companies to coat their triathlon suits with e.g. Teflon and to laminate the seams instead of sewing them. Therefore, air can be trapped inside these suits to alter the float and the overall drag can be reduced as well. Thirdly, even though the fit of the garment should be very tight to minimize the drag, the garment should not restrict the movement of the athlete resulting in a greater energy expenditure. According to Jenkins and colleagues (2014), 90% of swimming performance is done by arm work but the extensive range of motion of the arms and shoulder in all planes implies an undoubted critical area in terms of clothing fit and movement. Discomfort and higher energy demands can result from the fact that the body dimensions change as soon as the body moves whereas the clothing does not. On one side of the flexing joint the total length of the body surface increases and on the opposite side it shortens. In terms of the shoulder girdle this change in length corresponds to 13-16% (Hatch, 2006).

To ensure comfort and maximize the athlete’s performance, clothing in general can be adjusted in five different ways: 1) by use of loose clothing; 2) by unattached areas between garments (separates); 3) by open areas in the garment; 4) by use of flexible materials in tight fitting clothing and 5) by design features in critical areas such as elastic inserts under the arms (Ashdown, 2011). The first two techniques can be neglected in the case of triathlon suits, because these would significantly increase the drag while swimming. Open areas in the garment are used in the two-piece and sleeveless triathlon suits (Figure 2, A and B). As these do not cover the arms at all and are cut out widely around the shoulders, the movement of the arms is not restricted at all or only minimally. The short-sleeved triathlon suit (Figure 2, C) covers the whole shoulder and upper arm and therefore needs to make use of flexible materials in that region. According to Hatch (2006) the degree of flexibility in active, form-fitting clothing needs to be in the range of 30-50% measured in percent of elongation. This can be achieved by the right yarn processing (e.g. knitted fabrics have a higher stretch than woven fabrics) or with the addition of elastic fibers such as elastane. Essential for each listed type of performance optimization via garment is an appropriate fit. This includes a proper ease, which is the added length of the fabric in comparison to the body shape, and a proper set, which refers to the “balance” of the garment that keeps it in place in a way that gravity and friction do not displace the garment on the body. The process of pattern making can be quite challenging considering the wide variety of body measurements in the population (Ashdown, 2011). The use of two-piece suits can be advantageous in this respect. If an athlete has different sizes in upper and lower body, he can assemble his garments as desired. For this paper, 10 online shops of common triathlon companies were reviewed and none of them provided such a customization regarding sizing for their sleeveless or short-sleeved suits.

Figure 2. The three common types of triathlon suits. A: Two-piece triathlon suit. B: Sleeveless triathlon suit. C: Short-sleeved triathlon suit.

CYCLING:

REGULATIONS:

Cycling during triathlon is usually held on streets that are closed for the normal traffic. The common distances vary from 20km (sprint distance) to 180km (long distance). In general, there are two different kinds of competition modes: Draft-legal and draft-illegal competitions. The regulations depend on the athlete's racing category and distance to ride (Table 3).

	Junior/Youth	U23	Elite	Age Group
Sprint Distance	Legal	Legal	Legal	Both options
Short Distance	/*	Legal	Legal	Illegal
Middle/Long Distance	/*	/*	Illegal	Illegal

Table 3. Drafting regulations depending on race category and competition distance (ITU, 2018). *This race distance is not carried out for this category (ITU, 2018).

The permission or the prohibition of drafting during a triathlon has a great influence on the athlete's material to be used. However, the regulations resulting from the drafting specifications are mainly limited to the design of the bike and shall not be discussed in this essay. Accordingly, the abovementioned rules for triathlon suits will be maintained and also apply to the cycling part.

TECHNICAL POSSIBILITIES:

In cycling in general, wind drag accounts for up to 90% of the total resistance depending on different parameters such as the speed of the cyclist, the body and its position on the bike and the design of the equipment (Kyle, 1979). By drafting in the slipstream of another rider, the overall drag can be cut down by up to 40% (Olds, 1998). Derived from that, one can conclude that aerodynamics in cycling is one of the most important key factors and becomes even more important when slipstream riding is prohibited, which is why the competition mode plays such an important role. According to Martin and colleagues (1998), the general drag equation from basic fluid mechanics can also be applied to cyclists:

$$F_D = C_D * A \frac{1}{2} \rho U^2 \quad \text{with} \quad \rho = \frac{p}{R_S T} ,$$

where F_D is the aerodynamic drag force, C_D is the drag coefficient, A is the frontal area, ρ is the air density and U is the wind speed, p is the air pressure, R_S is the specific gas constant and T is the temperature. The drag force increases with the square of the wind speed, which is why aerodynamics becomes increasingly important the higher the velocity of the rider is. Athletes typically face high speed situations during level and downhill riding.

With the help of technologies, the overall drag force can be reduced by reducing the frontal area (tight fitted clothing has a smaller frontal area than loose clothing) and improving the drag coefficient. The basic mechanism that skin suits use to gain aerodynamic benefits is to decrease the flow separation as much as possible or to move it towards the lower back of the rider. This reduces the wake, i.e. the region of disturbed flow behind the body, significantly and therefor the aerodynamic drag in general (Crouch et al., 2017). The overall gain in performance is depending on many different parameters including fiber material, yarn type, fabric type (i.e. stitch pattern, density, thickness and porosity), seam positioning, coatings, covered area and fit (Brownlie et al., 2009). In areas of attached flow, smooth and/or coated fabrics should be used to reduce skin friction which refers in this case to the resistant force exerted on the rider's body as the air moves on the surface. This can be neglected in areas of separated flow such as the lower back so that the material can be designed to improve other parameters such as higher stretch to not impair the athlete's movement. The seams should be aligned with the airflow and the overall coverage should be as high as possible, which is until the elbows and knees according to the ITU competition rules. However, effective reduction of air resistance can only be achieved by tight fit and few material wrinkles. Due to the different body shapes of the athletes, it is probably not possible to choose a certain suit as the overall best, but an individual testing for the optimal suit is absolutely necessary (Brownlie et al., 2009).
In 2016, STAPS, an independent company that provides bike fittings and performance diagnostics in triathlon, made an aerodynamic testing inside a velodrome and published their data. An athlete rode with 11 different sleeveless and short-sleeved triathlon suits and a long-sleeved time trial suit as a reference at three different speeds (36km/h, 40km/h and 45km/h). Throughout the test, pedaling power was measured. The data show that the

reference suit performed best and all short-sleeved skinsuits performed better than the sleeveless ones. The difference in pedaling power between the best and the worst triathlon suit tested by STAPS was about 3.5% at 45km/h (Figure 3). Assuming that this athlete is able to cover a long-distance race (180km) with an average of 300 Watts, this would correspond to a difference of about 4 minutes (4:14:54h vs. 4:18:41h). It can be assumed that the benefit of the best aero suit over two-piece suits would probably be even greater due to the additional seams which are not in the airflow direction. Obviously, the testing carried out by STAPS is not a scientific study and only a single athlete has participated, which is why one should not give too much weight to the individual values. However, this data can serve as an example on how triathlon suits can optimize performance and to what extent the effects can be expected.

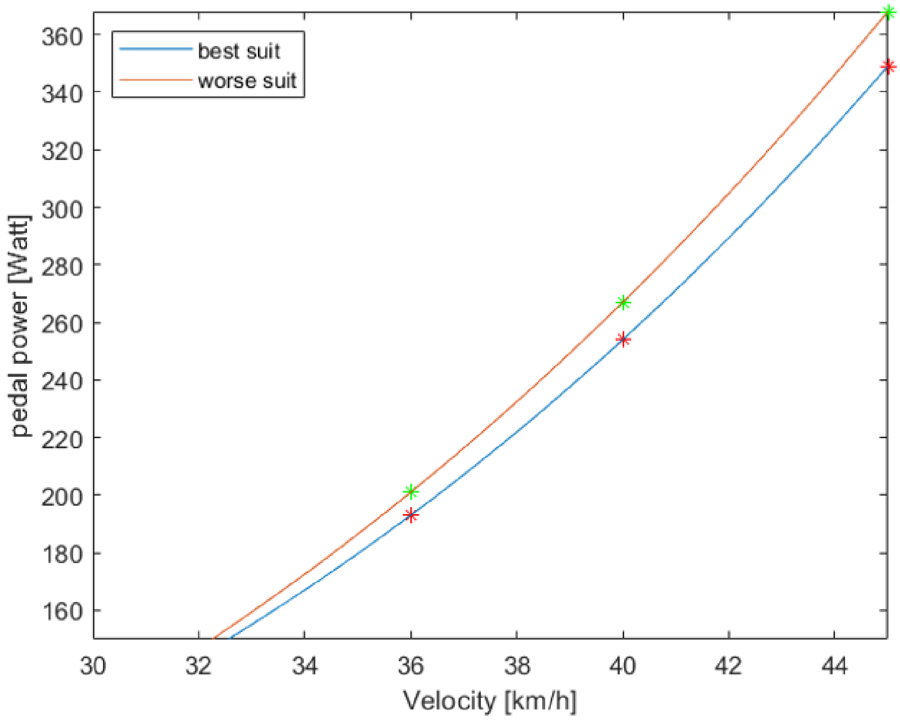

Figure 3. Interpolation of the pedalling power as a function of the riding velocity of the best and the worst triathlon suit (Modified from STAPS, 2016).

The performance of triathletes depends not only on mechanical factors, but also on physiological and psychological ones. The actual endurance capacity can obviously not be increased by a suit, but it can help to maintain the athletic performance longer regardless of environmental influences. In order to achieve maximum athletic performance, it is important that the athlete feels positive emotions and is in a general state of well-being. The basis for this is physical comfort. (McCarthy, 2011). For example, the padding of a triathlon suit while cycling plays a crucial role in comfort and prevention of overuse injuries and disorders (Leibovitch & Mor, 2005). By sewing seat cushions into the crotch of the suit, chafing can be reduced, the pressure on the saddle can be distributed over a larger area (pressure distribution in the spatial dimension) and impacts can be absorbed (shock attenuation in the temporal dimension). These pads consist either of additional fabrics, foams or gels, but are usually smaller than in isolated cycling competitions, so as not to impair subsequent running. However, the athlete can not only be brought out of this positive state by an uncomfortable sitting position, but also by thermal stress. This has not only psychological, but also physiological effects on the athlete's performance. Thermoregulation includes all mechanisms of the body to maintain a constant core body temperature of about 37 ± 1-2°C, may it be in cold or in warm climatic conditions (Cheshire, 2016). Those mechanisms cover heat production from metabolism and heat gain from environment, as well as loss of heat by convection, conduction, radiation and evaporation (Gavin, 2003). Particularly when cycling, high convection combined with evaporation and the strict clothing regulation regarding sleeve lengths can lead to severe heat loss of the body in cold environments. In extremely warm and humid environments, cycling can also cause body temperature to rise. However, this will be discussed later in the section 'Running', as the problem is more pronounced than with cycling due to the lower wind speeds and the resulting lower convection. An important factor in clothing thermoregulation is the unit 'clo' which is an index of the thermal resistance of a garment. One clo describes the clothing which is necessary to maintain a comfortable state at rest when the ambient temperature is 21°C. During exercise at temperatures of 0° and no wind, the human body is able to maintain the body temperature with clothing of one clo. If the wind speed increases, and it does so in any case during cycling due to the airflow, clothing with greater thermal insulation is required. But choosing the right type of garment can be quite challenging due to the difficulties to maintain balance between heat production during exercise and heat dissipation to the environment. Too little clothing can lead to hypothermia and too much clothing can lead to an increase in body temperature and excessive sweating. In both cases, comfort suffers severely and the endurance performance decreases. The ideal winter clothing therefore blocks the movement of air in dry, cold ambient conditions but supports water vapor escape through the clothing when sweating, e.g. with the help of the capillary effect (Gavin, 2003).

RUNNING:

REGULATIONS:

Running in triathlon is usually held on streets or pathways that are closed for the normal traffic. The distances vary from 5km (sprint distance) to 42.2km (long distance). In contrast to swimming and cycling, there are no special competition variations that could influence the choice of the equipment. Contrary to the other two disciplines, the rules concerning clothing are relatively open: The torso must be covered, in any other view the athlete may freely choose his garment (ITU, 2018).

TECHNICAL POSSIBILITIES:

That the athlete can freely choose his clothes during running particularly means that the athlete is allowed to change or add clothes during the second transition in order to be better adapted to climatic conditions. This regulation makes a closer look at triathlon suits for cold conditions, as it has been done for cycling, obsolete. This section will therefor deal with thermoregulation under hot and humid climatic conditions. The optimal ambient temperature for endurance exercises is approx. 10-12°C, this could be shown by Galloway and Maughan (1997). They examined the time until exhaustion in runners running at 70% of the maximum oxygen uptake at different temperatures on the treadmill. Stronger heat production induced by faster running and/or higher outside temperatures resulted in a steeper increase in body core temperature and a decrease in performance. The higher the load, the ambient temperature and the humidity, the higher are also the sweating rates. The maximum rate is 3 – 4 liters per hour (Weineck, 2010). Since the convective airflow during running (~3.3m/s) is significantly lower than during cycling (~9.7m/s, depending on the performance velocity and wind conditions), evaporation of sweat becomes the most important mechanism of the body to release heat. Any type of clothing represents a layer of insulation and therefore acts as a barrier to heat transfer and vaporization, leading to a reduction in cooling efficiency. However, this should not be understood as meaning that the fabric should absorb the sweat. Even if the removal of fluid from the skin leads to an increased comfort, to achieve a useful cooling effect sweat has to evaporate directly from the skin. Therefore, the garment that represents the least resistance to evaporation is the most suitable for running in warm and humid conditions and not the one that dries the skin the fastest (Gavin, 2003). To improve the breathability of triathlon suits, special types of fabrics can be used, such as mesh or mock eyelet constructions. In terms of thermoregulation, these perform better than plain jersey or tricot fabrics (Watson et al., 2018). Nevertheless, the covered area should be as small as possible to reduce the overall insulation and increase the cooling efficiency as none of these fabrics provides perfect breathability (Gavin, 2003). When examining the thermoregulation of triathlon suits, it is important to look not only at individual fabrics, but also at their placement, as well as the overall design and single construction elements such as zips, rear pockets and cycle pads. All of these have important functions such as better fit, nutrition and comfort, but also represent greater barriers to heat transfer and evaporation due to additional layers of fabrics or padding. The number, sizes, shapes and materials of these elements determines the loss of performance in regards thermoregulation (Watson et al., 2003).

CONCLUSION:

As shown in the individual sections, the requirements for triathlon suits are very broad due to different external media, travel speeds and movement patterns. Therefore, it is almost impossible for developers to design the perfect triathlon suit, but it is usually the task to make compromises in terms of functionality. Differences in demands between the first two disciplines and running are particularly critical in this respect. The hydrodynamics required for swimming and the aerodynamics required for cycling, which to a large extent influence the athlete’s performance, go hand in hand as both are based on fluid mechanics. In both cases, performance can be improved with the largest possible covered area, tight fit, seam positioning in flow direction, seam lamination and coating of the material. Due to their nature, however, these properties are associated with a limitation of breathability. If the competition to be completed takes place under warm and humid conditions, this can quickly lead to impairments of the athlete's performance due to overheating and dehydration, especially when running.

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