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Method Development and Validation for Front Crawl Swim Technique Evaluation.

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"…And now I try hard to make it, i just wanna make you proud, I'm never gonna be good enough for you…and you can't change me …I'm sorry I can't be perfect …" Simple Plan Perfect

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Abstract

Nowadays the spread of wearable technologies is in a continuous expansion in every industrial field. The biggest innovation brought by wearable technologies is their simplicity of utilization and their comfort. In particular, when talking about technologies for sport, it is easy to think how the presence of big sensor or devices on the athlete body surface would avoid a physiological movement. On the contrary, if the sensors and their microcontrollers are integrated, as far as possible, in the technical clothes, the device let the athletes be free from any impediment. This can be possible thanks to the invention of MEMS technologies and the creation of miniaturized sensor.

At the beginning the interest in wearable device was mainly oriented to medical applications under the impulse giving by the attempt to involved the user and their families in prevention, diagnosis and treatment of various kind of pathologies. This let the rise of Wearable Biomedical Systems (WBS).

The example given by this kind of device in the health care field makes the market think about a possible application in the sport and movement analysis area where often it is difficult to have a quantitative data with portable and low cost technology. The creation of wearable devices for sports evaluation brings many advantages:

1. They help trainers in the quantitative evaluation of technical movement so that they can prepare the athletes with training session supported by a solid numerical evidence. This also let the athletic trainer to assess improvements and the quality of technical gesture execution;

2. These device make people to be more active and to do exercises with an electronic supervisor so that people can do their exercises in safety and keeping trace of their health status. This has also a positive impact on the general healthiness of the population;

3. Wearable devices let the movement be more ecological: there aren't cables or other impediments for the athletes movement.

Considering swim, we can affirm how it requires complex movement supported by a really complex biomechanics. Furthermore we have to consider also the particular environment in which swimmers has to train especially for the presence of water. This two features make complex the development of a such devices.

Many are the already existing devices on market but, most of them, are not able to support trainers in an accurate evaluation of the athletic gesture. For example, don't give any information about heart rate or energy consumption, and don't give the opportunity to see any data in real time.

In this thesis work, that is part of a more complex project developed by the Sensibilab of Politecnico di Milano, the aim was to realize an algorithm able to analyze front crawl style and give to the trainers data about the athletes performances using only the accelerometer's data. It is possible to divide the work in two parts: in the first one it has been developed the algorithm and a simple GUI (*Guided User Interface*) realized with Matlab environment on the basis of a first acquisition made by the lab's team, while, in the second one, we have collected data with specific protocol and setup with the aim of evaluating the algorithm. This was possible thanks to the collaboration of the sport center Seven Infinity of Gorgonzola (Milano) that gives us the opportunity of testing the device on their Master athletes. In particular, we concentrate our attention on the temporal indexes validation, as laps time and inversion duration, and on the number of strokes giving by the algorithm. Result show very good results in lap time and number of strokes detection. Considering only number of strokes detection, we have also detected an high stroke sensitivity. However, in inversion duration, results are quite good but they can be improved so that the algorithm can have a better performance.

We have also asked to trainers their opinion on our project with a questionnaire. Results show that our work is appreciate by the most of them and that the way we're follow is the right one.

This thesis offers a solid basis on which can be developed a wearable and reliable device but it has to be improve and complete in every parts. It is also necessary to extend the evaluation to the other swimming styles and integrate information about heart rate and energy consumption so that the coach can have a complete feedback on the athlete status. Maybe, it would be interesting evaluate different communication protocol thus having a real time feedback during the training session.

The present work is organized in five chapters:

- Chapter one gives a general introduction on the history, biomechanics and techniques of swimming styles;
- Chapter two shows a panoramic on the devices on market showing their lacks, pros and cons. Later are presented the architecture of the used hardware and of the designed algorithm;
- In chapter three are described materials and methods for the validation trials and the statistical indicators and methodologies exploited to

compute results;

- Chapter four shows results of the device's validation and the discussion about them;
- Chapter five has the purpose to show to the reader the opinion of interviewed coaches, comments and future perspective of the whole project.

Sommario

Oggigiorno lo sviluppo delle tecnologie indossabili in ogni campo tecnologico è in continua espansione. La più grande innovazione portata dalle tecnologie indossabili è la loro semplicità e comodità di utilizzo. In particolare, quando parliamo di tecnologie per lo sport, è facile pensare come la presenza di sensori con dimensioni elevate o dispositivi posti sul corpo dell'atleta, potrebbero ostacolare il suo movimento fisiologico andando ad alterare il pattern dell'esercizio atletico. Al contrario, se i sensori e il loro microcontrollore sono integrati il più possibile negli indumenti tecnici, il gesto atletico sarà completamente avulso da qualunque impedimento. Questo è stato possibile grazie all'invenzione della tecnologia MEMS e alla creazione di sensori miniaturizzati.

All'inizio l'interesse per i wearable device era principalmente orientato alle applicazioni mediche sotto l'impulso dato dal tentativo di coinvolgere l'utente e la sua famiglia nella prevenzione, diagnosi e trattamento di svariate patologie. Ciò portò alla creazione dei Wearable Biomedical System (WBS).

L'esempio dato da questo tipo di dispositivi nell'healt-care, portò il mercato a pensare ad una possibile applicazione di questi dispositivi nell'area dell'analisi del movimento e dello sport dove spesso è difficile avere dati quantitativi con una tecnologia portatile e a basso costo. La creazione di dispositivi indossabili per la valutazione dello sport ha portato diversi vantaggi:

1. Aiutano gli allenatori nella valutazione quantitatica e oggettiva del movimento tecnico in modo tale che essi possano preparare gli atleti attraverso sessioni di allenamento supportate da una solida evidenza numerica. Inoltre ciò permette all'allenatore di attestare i miglioramenti e la qualità dell'esecuzione del gesto sportivo;

2. Questi dispositivi spingono le persono ad essere più attive e a praticare esercizi fisici con un supervisore elettronico, in modo tale da svolgere l'attività in sicurezza e tenendo traccia del proprio stato di salute. Questo ha anche un impatto positivo sulla salute della popolazione in generale;

3. I wearable devices permettono al movimento di essere il più naturale possibile: non ci sono cavi di alcun tipo o altre tipologie di impedimenti al movimento degli atleti.

Considerando il nuoto, possiamo affermare come esso richieda l'esecuzione di movimenti complessi supportati da una anch'essa complessa biomeccanica. Inoltre è necessario considerare il particolare ambiente in cui i nuotatori devono allenarsi caratterizzato principalmente dalla presenza di acqua. Queste due catatteristiche rendono complesso lo sviluppo di tali dispositivi per la valutazione del nuoto.

Molti sono i dispositivi già presenti sul mercato ma, la maggior parte di essi, non sono in grado di supportare gli allenatori in un'accurata valutazione del gesto atletico. Per esempio alcuni di essi non danno alcuna informazione sulla frequenza cardiaca sul consumo di energia e non danno nemmeno l'opportunitò di vederi i dati in real time.

L'obiettivo di questo lavoro di tesi, che rientra in un più complesso progetto sviluppato dal laboratorio Sensibilab del Politecnico di Milano, era quello di realizzare un algoritmo che fosse in grado di analizzare lo stile libero e di dare informazioni all'allenatore sulle performances sportive degli atleti usando solo le informazioni ottenute dagli accelerometri.

É possibile dividere il lavoro in due parti: nella prima sono stati sviluppati in primis l'algoritmo e poi una semplice GUI (*Guided User Interface*) in ambiente Matlab sulla base di un'acqusizione fatta dal gruppo di ricercatori del laboratorio, mentre, successivamente, si sono acquisiti dati con un protocollo e un setup realizzato ad hoc per la valutazione e validazione delle prestazioni dell'algoritmo. Questo è stato possibile grazie alla collaborazione con il centro sportivo Seven Infinity di Gorgonzola (Milano) che ci ha dato l'opportunità di testare il dispositivo sugli atleti della categoria Master. In particolare ci siamo ci siamo concentrati sugli indici temporali, come i tempi di vasca e la durata dell'inversione, e sul numero di bracciate ottenuti in uscita dall'algoritmo in quanto molti degli altri indici ricavati si basano su queste misure. I risultati ottenuti sono molto positivi per quanto riguarda i tempi di vasca a il numero di bracciate. Considerando unicamente il numero di bracciate ottenute, abbiamo riscontrato un'alta sensitività nell'individuare le bracciate. Ciononostante, i risultati per quanto concerne la durata dell'inversione, sono abbastanza buoni ma hanno ancora un ampio margine di miglioramento.

Abbiamo inoltre chiesto la loro opinione sul nostro progetto agli allenatoti con un questionario pensato appositamente. I risultati mostrano che il nostro lavoro è apprezzato dalla totalità di essi e che il progetto sta percorrendo la giusta direzione.

Questa tesi offre una solida base su cui può essere sviluppato un dispositivo affidable ma molti sono i miglioramenti e le integrazioni da realizzare.É necessario inoltre estendera la valutazione agli altri stili e integrare le informazioni sul ritmo cardiaco e sul consumo energetico in modo tale che l'allenatore possa avere un feedback completo sulla preparazione fisica dell'atleta. Potrebbe inoltre essere interessante valutare diversi protocolli di comunicazione in modo da avere un feedback in real time durante la sessione di allenamento.

Il presente lavoro è organizzato in cinque capitoli:

- Il capitolo uno dà un'introduzione generale sulla storia, sulla biomeccanica e sulle tecniche dei diversi stili nel nuoto;
- Il secondo capitolo mostra una panoramica sui dispositivi sul mercato, mostrandone i difetti, i pro e i contro. In seguito sono presentate l'architettura dell'hardware e dell'algoritmo realizzato;
- Nel terzo capitolo sono descritti i materiali e i metodi per le prove di validazione del dispositivo e le metodologie statistiche e gli indicatori utilizzati per il calcolo dei risultati;
- Il capitolo quattro mostra i risultati della validazione del dispositivo e la loro discussione;
- Il capitolo quinto si propone di mostrare al lettore l'opinione degli allenatori intervistati, i commenti e gli sviluppi futuri dell'intero progetto.

Capitolo 1

Introduction

1.1 Swim:Definition and History

The definition of the term “Swim” is [25]:

> *A coordinated series of movements, made by men or animals, so that they can move on the water surface or underwater.*

In this way we can observe how, with the verb *to Swim*, we refer to a large class of movements made in water. This definition has probably his roots in the history of this sport.

The genesis of this sport [22], although we can affirm it wasn't perceive as a real sport, ascends from the Prehistorical Age. Archeologists know that humans developed watercraft by 40000 years ago, and so it's reasonable to assume people were swimming by that time[1]. Many of this swimming activities seem to have been part of religious rituals, recreation, or military maneuvers. William Wilson in 1883 said:

> “*Swimming is one of the oldest arts, if we are to form an opinion from the fact that no trace of its origin, discovery, invention or improvement is to be found in any of the ancient writings*”.

In particular the existence of Swim, as the capability of a person to move in water, is attested by mural paintings and graffiti (1.1) of the fifth century B.C. [29].
From the sparse description on record, early attempt at swimming probably consisted of random arm and leg movements with no specific technique; otherwise, we know little of the early history of human swimming. The first human swimmers most likely lived by the sea or near warm rivers. Five thousand years ago humans learned to divert rivers such as The Nile, the Euphrates, and the Indus, and it's likely that people living in these regions were at home in the water and swam frequently.

[1] Nemecek, 2000

Figura 1.1: Prehistorical graffiti of swimming people.

In the ancient world, diverting rivers to protect city-states led to swimming for military purposes. Bas-reliefs housed in the British Museum show a river crossing by Assurnasir-pal, King of Assyria, and his army. Nineteenth-century observers thought the reliefs showed soldiers swimming either side-stroke or the trudgen stroke, while 20^{th} century observers concluded that the Assyrians were actually swimming crawl style.

Later, with romans, swim becomes a real sport: in roman culture swim was considered as a real agonistical sport and was used also for the training of soldiers. The Baths of Caracalla and other baths built by the Romans were enormous, but the swimming tanks set aside for actual swimming were very small. Those at Pompeii were only 13 feet wide, and Cicero complained that he needed a wider pool to avoid hurting his hands against the wall. However, the baths of Mohenjo-Dario in the Indus valley (in today's West Pakistan) were somewhat larger and were the birthplace of a form of synchronized swimming that served a religious function [2]. *Cicero* in the oration *Pro Caelio*, also refers to swim when he talks about a crowd of people that moves toward the Tevere river to swim. Before him a nobleman of the Middle

[2] Cottrell, 1960

Kingdom of Egypt (2160-1780 B.C.) proudly recorded that his children took swimming lessons with the king's children, but no mention is made of skills being taught[3]. One of the beautiful and rare written passage was left to us by Manilius, a 1st century Roman poet, who waces lyrical an the pleasures of swimming[4]:

For just as the dolphin glides through the water on swift fins,
now rising above the surface and now sinking to the depths,
and piles up waves and sends them off in circles,
just so will each person born under the sign of the Dolphin fly through the waves,
raising one arm and then the other in slow arcs.

Later there was also the birth of real and specific manuals and writings on this theme. In 1538, Nicolaus Wynman, wrote a manual called *Colymbetes, sive de arte natandi dialogus etfestivus et incundus lectu* in which he described different styles of swim, mainly back crawl and breaststroke. Afterwards many authors, as Sir Everard Digby [5] in London, Melchisédch Thévenot [6] in Paris and Oronzio de Bernardi[7] in Naples wrote about the art of swim.

In the Middle Ages, swimming became unpopular throughout Europe because people believed water helped spread plague and other common epidemics. When people did swim, they preferred a form of breaststroke that kept their faces out of water. Not until the second half of the 19th century was prejudice against swimming largely overcome.

In 16th and 17th century Europe, the breaststroke was performed with the head held high and completely out of the water[8]. Instead of using a frog kick, propulsion was applied with the insteps and not the soles of the feet[9].

Although the big numbers of written works and proofs of the existence of Swim, the modern concept of this sport originates only later, and exactly two century ago: indeed, before organized competitive swimming started in England, there was little need to develop methods beyond those that came naturally.

1.1.1 Modern Swim and the Birth of Swimming Styles

The "modern swim" [20] [29] [22] and the technical development of swimming, didn't start until the mid 19th century with the building of swim-

[3] Cureton, 1934

[4] Marcus Manilius(circa 14 A.D.), from Astronomica, an unfinished poem on astronomy and astrology

[5] cfr.*De arte natandi libri duo*, 1587

[6] cfr. *Art de nager*, 1696

[7] cfr. *L'uomo galleggiante, o sia l'arte ragionata del nuoto, Stamperia Reale 1794*

[8] Thevenot, 1699

[9] Muths, 1798

ming pool, the invention of the stopwatch, and the beginning of competitive swimming as a formal sport.

Early in the 19^{th} century, breaststroke swimmers adopted a frog kick in which the ankles were dorsi-flexed and propulsion developed by pressing the soles of the feet against the water [10]. As the stroke technique developed, so did the drills used by swimmers, although some of these drills were strange (Figura1.2).

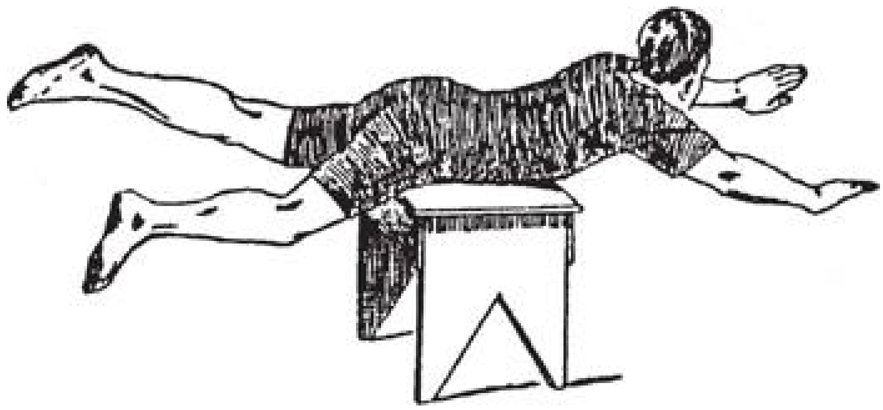

Figura 1.2: In the 19^{th} century, breaststroke drills were weird and wonderful.From Dalton 1899.

There were lots of discussions about which was the best kick: many swimmers thought using the soles in the frog kick yielded more propulsion instead of spreading the legs and then straightening them before closing in a tight wedge (Figura1.3).

These discussions, marked the beginning of technical thinking and the starting point of a new thinking related to the improvement of propulsion. From that moment swimmers understood what can be obtained from a slight change of technique.Nowadays this awareness allows experienced and capable coach to gain better performances from their athletes in competitions.

The National Swimming Society, organized in 1837 in London the first programmed competitions. The first competitive swimmers, as we've said before, were more intent on developing good-style rather than speed. Graceful and elegant movements, with a minimum of splashing, were considered the hallmarks of style by the early exponents of the sport.

At that time, the sidestroke became the standard racing style: they move in water with both arms remained submerged throughout, and the legs performed a wide scissors kick with opening and closing movements that resembled walking (Figura1.4). It was only in this period that swimmers

[10]Counsilman, 1968

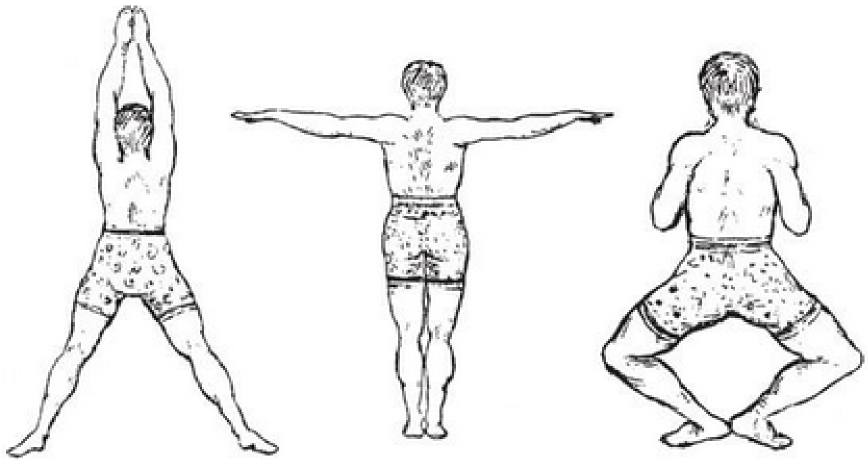

Figura 1.3: kick of breaststroke in 19^{th} century. From Wilson 1883.

found they could reduce resistance by recovering one arm over the water instead of underwater as in the breaststroke. This stroke, precisely, was called *English overarm sidestroke*.

Figura 1.4: Mechanism of the side stroke. From Sinclair and Henry 1903.

If we observe Figura1.4 it's easy to understand how sidestroke evolved from breaststroke: it's like swimming breaststroke with the body turned on its side. In this way swimmers encountered less water resistance.Sachs in 1912 said:

> *"It is necessary to cleave the water with the head or shoulder in order to avoid undue resistance."*

We can also distinguish an other kind of sidestroke style in which both arms were in water during movements of pull and recovery; this was known as the *underarm sidestroke* (Figura1.5).

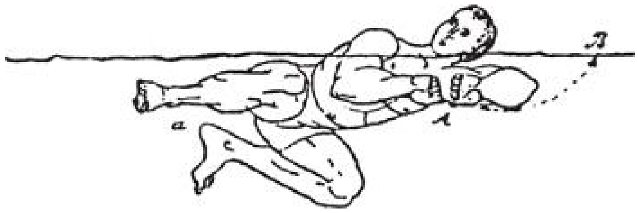

Figura 1.5: A subject swimming with underarm sidestroke. From Reichel 1897.

Realizing the superior speed of the English overarm sidestroke, racers abandoned the underarm stroke and recovered one arm over water[11](Figura1.6).

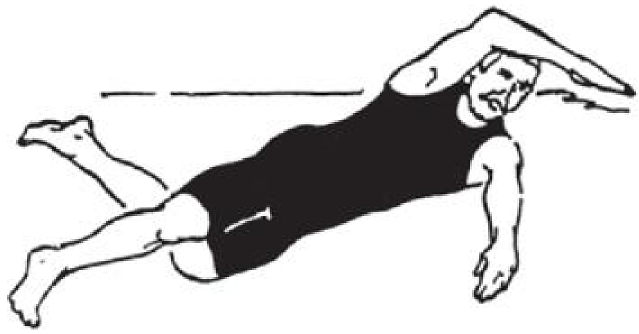

Figura 1.6: Mechanism of underarm sidestroke with one arm recovered over water. From Sachs 1912.

The kick used in this kind of style was a *screw-like leg kick* (Figura1.7)(scissors kick). This new style also let J.A. Jarvis marked supremacy in England. The adoprion of the English overarm sidestroke showed a growing awareness of the importance of decreasing resistance in proportion to speed. However, at this point, a full appreciation of the arms' potential for propulsion still did not exist.

[11]Counsilman, 1968

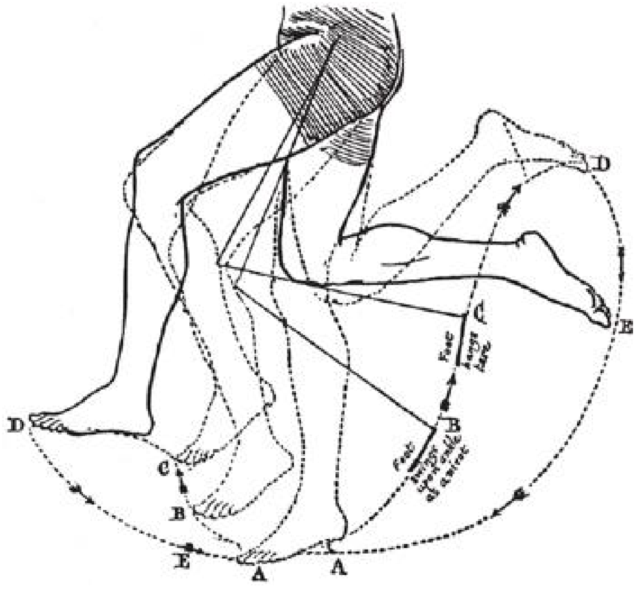

Figura 1.7: Jarvis new kick in sidestroke style. From Sinclair and Henry 1903.

In 1844, in the same city, took place an exhibition of American aborigines whose excellent throughouts astonished those present 'cause till that moment English was able only to swim with breaststroke and sidestroke style. In that occasion, aborigine swimmers was defeated by an English swimmer. Moreover the *strange style* would have not been considered because the Indians' more advanced overarm stroke were characterized by wild splashing. So their methods were dismissed by English as unworthy of imitating. Neither did the English know that across the broad expanses of the Pacific Ocean, the inhabitants of Polynesia and Melanesia had been swimming with overarm strokes for more than a thousand years. Only later this new style was called *crawl* and it revolutionized the world of competitive swim. In 1858, near Melbourne, took place the first international competition. It was an event based on a distance of 100 yard and it was called, for the first time, World Swim Championship. Swim, in 1896, became an Olympic sport.

In 1883, William Wilson said:

> *"another mistaken idea is that the propelling part of the kick is obtained from the soles of the feet; these mistakes to a great extent account for the too often unsuccessful efforts made by those who wish to teach themselves."*

In other words Wilson affirms how can be obtained a major propulsion leg kick because is easier to push the body forward than to pull it trough or along. Also marked the attention on the strength of the lower limbs: legs are stronger than the arms so it's more convenient to obtain more as possible, in terms of strength, from them.

At that time, styles were not like those we see nowadays. At the end of the seventeenth century, the most common styles were the over (abbreviation of *single over arm side stroke*), trudgen (by the name of his founder John Trudgen[12]) and the breaststroke.

The Over was a style based on a variant of sidestroke: rather than proceed with both arms submerged, swimmers, during the recovery phase, brings out from water his arm. In this way he can eliminate drag of fluid.

The trudgen style appeared first in a swimming race in England on August 11,1873.

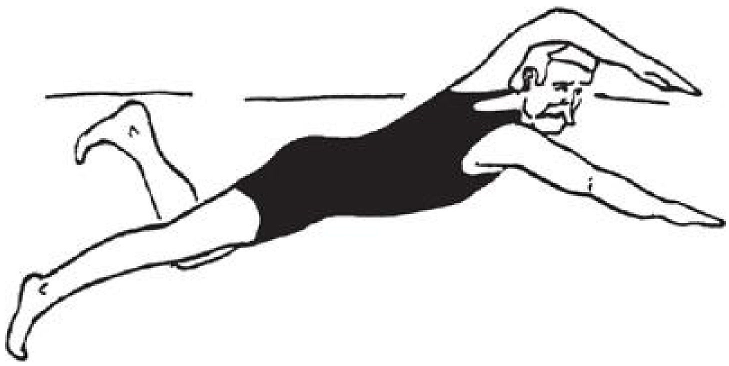

Figura 1.8: Trudgen stroke style.

The trudgen, instead of on one side, was a technique in which the swimmer proceeded adopting a ventral position, bringing out from water alternatively both arms as we can see in Figura1.8. Trudgen learned the South American Indian stroke from the natives. English spectators were startled when Trudgen won his first race, the English 160-yard handicap, with a most unusual stroke. The idea for a double overarm stroke came from observing his unusual technique, which later was to become the basic arm stroke of crawl style. What we said bring us to affirm how the trudgen style was the real predecessor of crawl style. The difficulty with the Trudgen stroke was that it lacked continuity; in fact, it was very jerky because it timed one breaststroke kick to every two arm stroke. For this reason the kick, originally performed with considerable knee-bend, was narrowed and the legs

[12] *John Trudgen was born at Poplar, London, on May 3, 1852, and went to Buenos Aires in 1863.*

were held straighter, but the timing of the side scissors kick still prevented a perfectly continuous arm action. Trudgen's championship swim was described in the *Swimming Record*[13]:

> His time was very fast, particularly for one who appears to know but little of swimming... I question, indeed, if the swimming world ever saw a more peculiar stroke sustained throughout a 160 yards race. Here we had a man swimming apparently easy, turning very badly, and when finished, appearing as though he could have gone at least another 80 yards at the same pace. His action reminds an observer of a style peculiar to the Indian.

trudgen became one of the speediest sprint swimmer of his time.As a result of Trudgen's influence, considerable experimentation followed with double overarm swimming, although many swimmers still whished to remain on their sides, however, because they feared that swimming in flat position on the chest would cause too much frontal resistance. There wasn't mention of a regular breathing method whithin the rhythm of the trudgen stroke: the next step would have been to learn to breathe in a regular rhythm with face-out-of-water inhalation followed by steady exhalation again as the face submerged. In the late 19^th century many forms of the trudgen stroke came to be swum by sprint swimmers and water polo players. However the stroke was so fatiguing and few swimmers could mantain it for over 200 yards. Many pros have said: "To imitate Trudgen... have degenerated Londoners to the level of mediocrity".

The turning point in the development of crawl stroke came when Dick Cavill realized that the side scissors kick actually retarded continuous propulsion. Furthermore, by the time, Cavill make a strange discover: after a few private time trials observing his brother, he was convinced that him could sprint faster without using his leg. Thus the scissors kick was radically wrong. At this point the question was: How to find a right kick?

A primitive form of crawl style was observed in the isle of Rubiana in Pacific Ocean from the Australian Harry Wickham. He noticed how swimmers can kick alternatively their foot up and down. Mr. Wickham taught this new style to his brother Alick who won a competition in Sidney. It was during this event that one of the competitors said: " *Look at the kid crawling!*".

It was only later that Dick experimented the new movement of legs and he was surprised by the results: the kick proved speedy from the very first trial.Nevertheless, when he tried it in a race, Cavill was defeated but it was important to underline the big value of the new stroke. At Rubiana there were many successes using this style after different changing in techniques. Soon the stroke (Figura1.9) invaded Europe, eventually reaching America in 1904.

[13]Swimming record, R.P. Watson, August 12 1873

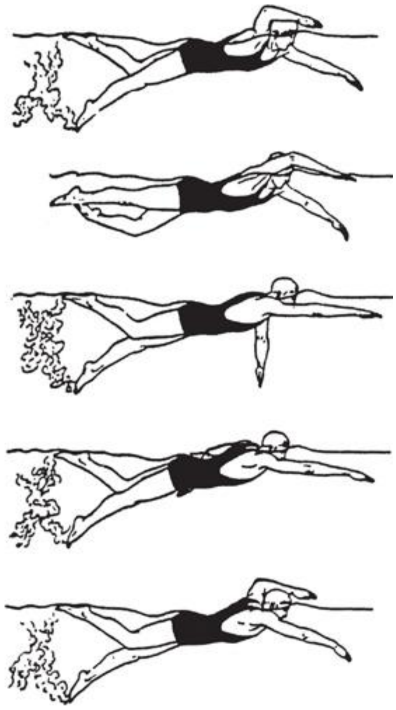

Figura 1.9: One version of the American crawl,1940. From Armbruster 1942.

There are two versions on how the term crawl stroke may have originated: one of them is that, as we've said before, George Farmer, a prominent Sydney coach, exclaimed the celebre expression see before. The other version is that 15-year-old Cavill, burrowed his head so deep below water's surfece while swimming the new stroke that he persistently swam over his rivals who complained that young Cavill was *"crawling all over me"*. However someone refers that the term crawl may have long been in common use to describe the dog paddle. In conclusion we can say that, nevertheless its origin, crawl was, and nowadays is, the most important swim style.

After that coaches realized the need to improve the efficiency of the crawl to enable its use for longer distances. The ability to breathe easily and regularly was the big problem. It was Cecil Healy, one of the great early Australian swimmers, to develop the idea of turning the face sideways out of water to inhale. She affirmed to had seen this kind of breath method in Hawaii from all native swimmers that used it naturally (Figura1.10).

Furthermore Handley (1918) added that not only did body position, balance and rhythm rely largely on efficient head turning mechanics while

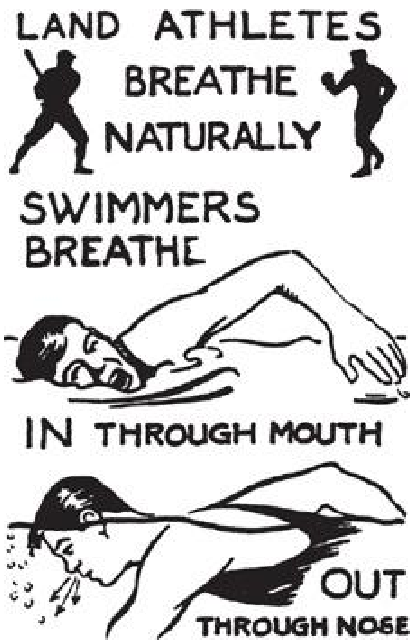

Figura 1.10: Crawl stroke breathe. From Bachrach 1924.

breathing but that the ability to swim longer distances relied on a regular supply of oxygen to the working muscles. The addition of improved breathing techniques to the American crawl soon enabled swimmers to establish records over the longer distances.

European leagues of swim, till 1920, had a bad organization: Olympiads of Athens in 1896 were challenged in sea, those of Paris (1900) in the river Senna,in Saint Louis in 1904 in an hot artificial lake and those challenged in London in 1908 in which swimmers was constrained to swim in a 100 meters pit made in a site of the Olympic stadium of Athletics. There were many other competitions made in similar condition, as those of Stoccolma in 1912 and Anversa in 1920, but in 1924, in Paris, at last, competitions were challenged in a real 50 meters swimming pool: from that moment on, swim challenges were disputed only with severe and fixed rules so that every form of empiricism were eliminate. At that time there were three types of styles: crawl, backstroke and breaststroke.
At the beginning of breaststroke style, as Frank Sachs in 1912 affirmed, spread between swimmers the idea that the strength of a style depended only on the leg stroke. As we can read in Sachs writing:

> “ . . . the legs were straightened and as wide apart as possible, before bringing them together very smartly and to as neary as

Figura 1.11: Breaststroke stroke in 1920s. From Bachrach 1924

possible make them touch ..."

This technique, known as *the wedge kick*, were abandoned and replaced by the *whip kick* in which the soles propelled instead of a closing of legs.

Bachrach didn't agree with usual frog kick taught at that time because the structure of a frog is too different from that of a human. This demonstrate that we can't swim like a frog. Bachrach's method of breaststroke kicking was to spread legs to a wide straddle position, with knees bent and turned out sideways. He said that this methot *instead of resembling the frog's kick, it is like the flapping of two fishes tails.* The negative point of this version of kick was that it merely washes the water sideways over the legs instead of directly backward.

Handley in 1918 improved this style: the arms were no longer swept back close to the surface until at right angles to the body. Instead he taught to take a shorter stroke and pull down as well as outward. Furthermore arms and legs didn't drive and recover together but alternately so that there was a more distribution of effort, constant propulsion and less stoppage between arm and leg movements. The outward and downward pull lifted the upper body higher: in this way the swimmer could inhale freely and deeply.

Additionally the shorter pull reduced the inward and forward movements resulting on a less resistance and a more powerful backward component.

Breaststroke, in 1920's, consisted of an alternate movement that involved subsequently a large kick and a large stroke with a contemporaneous inspiration phase. In the 1928 Olympics in Amsterdam, there were two leading male simmers: Tsuruta and Rademacher. With Rademacher and Tsuruta, we have the first modifications of the *old style*: they introduced a less large movement of legs with the joints of knees that goes deeper for the preparation of the kick and a stroke brought under the body rather than sideway[14] (Figura1.12). After that there were a continuous modification, as that described by Bela Rajki in 1956, of this style that culminated in a fusion of the actions of legs and arms without any pause.

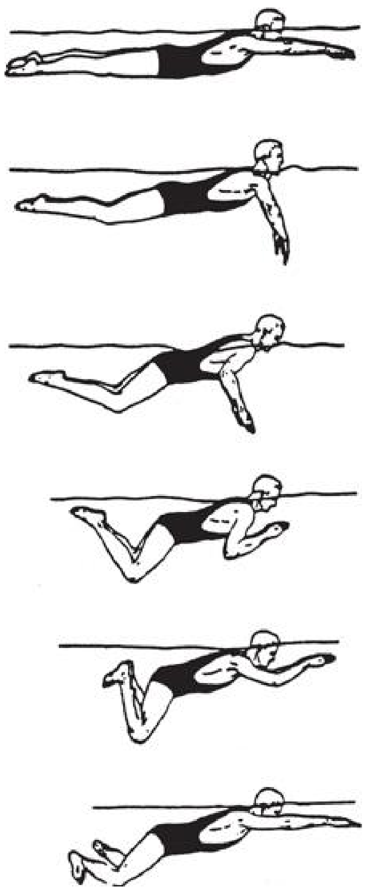

Figura 1.12: Breaststroke stroke in 1930s. From Armbruster 1942

[14] David Armbruster, 1942

During the 1930s there was the birth of an hybrid stroke that combined butterfly arm action with breastroke kick (Figura1.13). Rademacher was the first to introduce the *butterfly* style: he evolved the breaststroke style creating a new and useful movement.

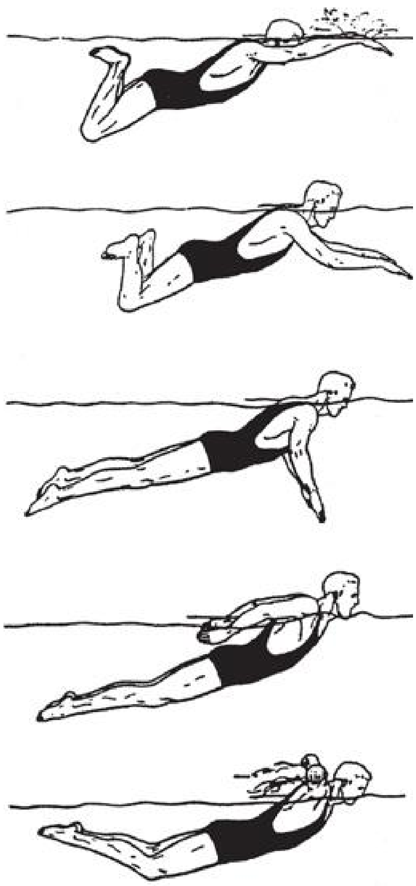

Figura 1.13: Butterfly-breaststroke style. From Armbruster 1942

in 1926, given that rules don't say anything about an hypothetical underwater restore phase, he tried to bring arms forward carrying them out from water as, for example, a double and contemporary crawl's stroke. He showed this technique also in the United States in 1927 but only in 1933 Myers use this style to compete in a 3x100 relay in New York. The *butterfly-breaststroke* became very quickly the fastest method of competing in swim races and breaststroke risked to become extinct. The new style was considered too heavy to use in a 200 meters competition. It was only in the postwar period that it was decided that a swimmer would had to swim the whole distance using only one of the two styles, instead of use a combination of them during the duration of the event. The first Italian swimmer to complete a 200 meters competition using only the butterfly style was Pigorini in 1947. After Olympiads in 1952, exactly in 1956, breaststroke and butterfly were definitively separated and recognized as single style. In a first time, because of some lacks in laws, a new trend rapidly developed in which swimmers took to swimming long distances underwater. They would surface only for a breath. To avoid this technique, FINA in 1957 legislated so that breaststroke would had been swum as a surface swimming with only one underwater pull and one kick allowed after the pushoff from the wall at the turn and an underwater glide allowed after the starting dive. Later there were many debates on what swimmer had or not to do during a competition to not be disqualified. Only in 1980 FINA Congress in Moscow, was able to overcome this problem. After breaststroke once more bacame a separate stroke, its evolution was characterized by an increased attention to streamlining the stroke, while also adapting it to different body types.They were developed many versions as those of American and the Australian swimmers, or that of the European swimmers with significantly different features in posture and mechanics of movement. Furthermore butterfly style give birth to dolphin style.

Dolphin was born from an idea of a group of athletes of introducing a vertical kick movement in place of the more conventional breaststroke kick. Nevertheless Henry Myers is generally credited with developing the butterfly stroke. In 1933, while swimming breaststroke in practice, as a novelty diversion he tried pulling his arms through to his hips and recovering them over the water like a double freestyle arm recovery. He was amazed to find he could beat his club's best breaststroke swimmers. Myers with Robertson, his swimming coach, decided to try out the stroke (Figura1.14) in the 150-yard medley event at the Brooklyn YMCA swim meet in December 1933 [15] and, surprisingly, he beat the favorite Wallace Spence.
In 1935, Jack Sieg, developed the skill of swimming on his side while moving his legs in unison and showed his speed potential by swimming 100 yards in 60.2 seconds. Dolphin kick is much faster when swum under the surface after the starting dive and when pushing off from the wall after the turn: swimming below surface eliminates wave drag (about 80% of overall drag). However this was prohibited by the rulebook: it was necessary to execute the same movements on the horizontal plane (legs moved in the vertical plane). This was no longer true when the division of the two styles was accepted: the vertical kick (like a double and contemporaneous crawl kick), was definitively introduced and we have the creation of a new recognize style. Promoters of this new kind of swim were Fejer and Tumpeck.

In *Colymbetes*, Wynman (1538), give the first reference to swimming on the back telling of a man on his back pretending to be a corpse and moving

[15] Colwin 1998

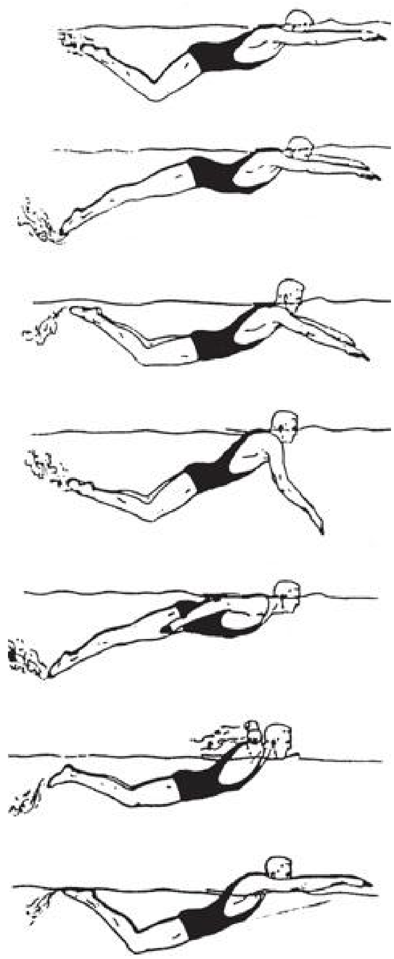

Figura 1.14: The early dolphin butterfly stroke. From Armbruster 1942

his hands with swift movements like birds do their wings.

After this first tribute of swimming on the back, there weren't any significant development in this style.*Backstroke* initially seemed to be a symmetric reverse breaststroke consisting of a double-overarm recovery and an upside-down breaststroke kick, performed in the same rhythm as breaststroke.

At the beginning of the 20^{th} century, H.J. Handy introduced a trudgen backstroke in which arm stroked alternately. Later Hebner, in 1912, introduced an alternatively arm movement (*back-crawl*) risking to be disqualified. More precisely he converted crawl stroke principles to swimming on back (Figura1.15).
With regard to the movement of the leg, firstly was like a "foot thrust". Then, in 1932, Japanese won the L.A. Olympiads showing a kick similar

Figura 1.15: Movements of Hebner's backcrawl. From Bacharach 1924

to that use in crawl style. A real innovation was brought by Adolf Kiefer in 1935, who introduced the backstroke flip turn instead of the deeper and more famous one that requires a great energy consumption. Furthermore we can affirm how Kiefer introduced a recovery with arms, elbows held straight, with a low lateral swing over the water. His technique, described by Armbruster (1942) became known as the "*Kiefer style*"(Figura1.16).

In 1951, Kiphuth and Burke described a bent arm pull in the backstroke: they referred to a style in which the swimmer moved with an alternate overarm action, synchronized with an alternate up-and-down beat of the legs, six kicks to a full cycle of the arms. The arm stroke started with the arm extended at full length behind the head and slightly outside the shoulder.

At conclusion of this paragraph we can say how swim is in a continuous evolution that, in past as nowadays, modifies his characteristics to evolve and let the swimmers gain the best performance, so the best time, with a less power and energy consumption. This is the reason why is necessary to comprehend the biomechanics of movement and give devices to the athletes to evaluate and attest their improvements and what they have to modify in order to obtain the best performance.

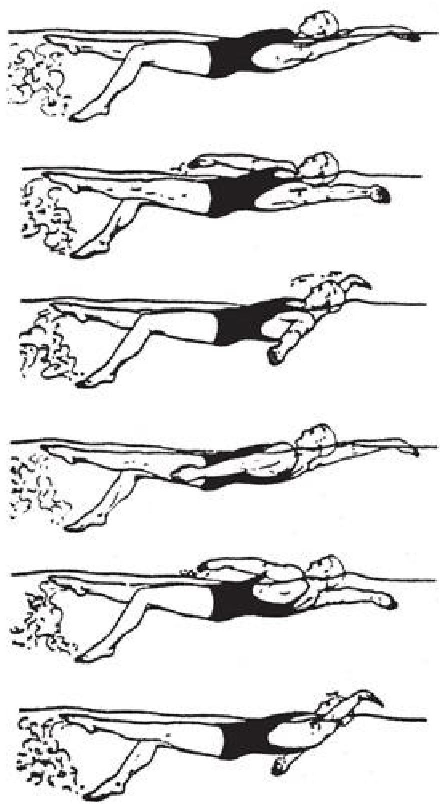

Figura 1.16: The Kiefer style. From Armbruster 1942

1.2 Styles: Qualitative description of Techniques

The description of swim mechanics was developed since the first recording device, as camera or video-recording instruments, become available. But only recently we have the opportunity of understanding the real movement made by athletes by the use of the ultimate generation devices for the swim analysis as waterproof cameras and system for movement analysis. One of the first system for the mechanical analysis of swimmers, was that used by Counsilman. It consists of flashing ligths attached to swimmer's hand to accurately measure the three dimensional path of swimming stroke and a grid system on the wall of the pool as a reference for stroke analysis and invented a "roll around" method for filming swimmers from directly below. Now we can, trough the use of these tools, describe exactly how athletes move in water. In this section we will consider only three style: this choice is made because, in this work, we developed a device able to analyze exclusively front-crawl, breaststroke and back-crawl style.

1.2.1 Crawl Stroke

In 20^{th} century, crawl underwent to a series of transformations bringing it to a new form of movement [22]. This new kind of technique is far from the painful efforts of the pioneers of crawl. It is characterized by split-second timing of the arms and smooth transitions from one phase of the stroke to the next. The body assumed in each phase a streamlined alignments that reduce resistance and prolong the momentum developed by each successive stroke.

From a lateral view (Figura1.17), the upper arms form an approximately 45 degree angle to each other as the left arm enters the water. The rigth arm has an elbow-up position that places the hand at an efficient angle to push water backward as the arm begins the power phase of the stroke.

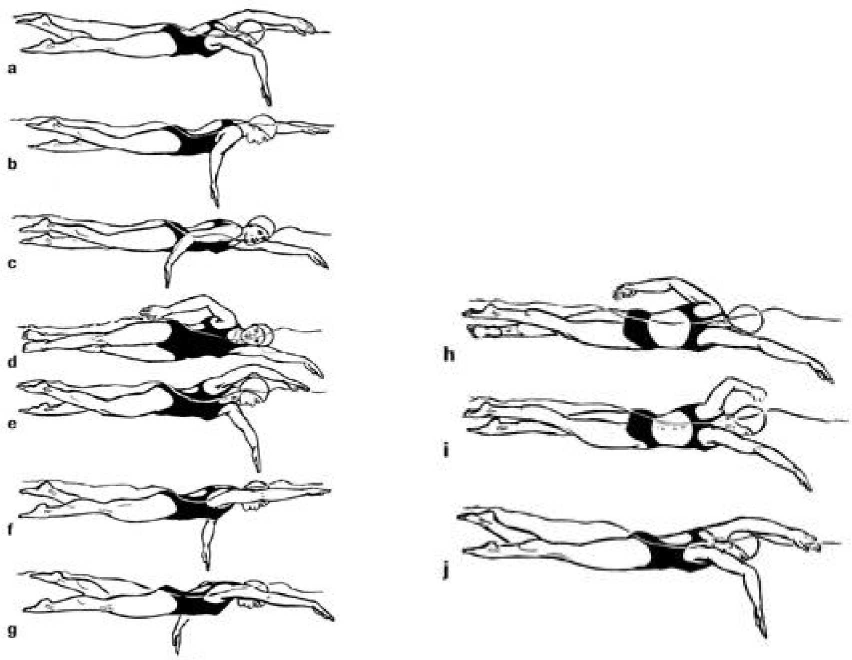

Figura 1.17: Crawl: side view.

In Figura 1.17.b the right arm is more accelerated than the left one which is completely immersed. The slower movement of the left arm helps retain the body's momentum. Later the left arm and shoulder gradually extend forward and begins a movement that displaces the body towards the left side.

The body weight shifts over the left arm when this starts to pull with the hand flexed at the wrist, applying pressure on the water as can be seen in Figura refcrawlside.c. The right arm is adducted as soon as the right hand and forearm complete the push (*duck foot action*). The face turns contemporaneously with the thrust of right arm.

Swimmer inhales as the whole body turns naturally along its axis (Figura refcrawlside.d). The recovery of the right arm is made with shoulder and elbow leading the action. It' s very important to underline that swimmer has not lifted the head to inhale. The face returns underwater with a faster speed than the previous recovery phase of the right arm and the swimmer can see the right arm underwater as it enters.

Now the right arm has completely gone underwater and the head remains centered in the long axis of the body (Figura 1.17.f). The body of the swimmer is positioned streamlined and balanced-head down, hips at the surface, leg action inside the body line. The left hand's acceleration is very high with respect to the other hand, which moves slowly ready to tilt the body over onto its right side (Figura1.17.g).

When the left arm completes its stroke and recovers, switches and tilts (Figura1.17.h). The weight of the recovery arm and the shift in in body balance provide powerful assistance to the start of the pull phase of the right arm. The posture of this arm is elbow up, hand flexed at the wrist. Now the right hand grips the water and the left arm, elbow higher than the wrist, reaches forward to the entry as the right arm moves into the pull (Figura1.17.i). The body has a perfect balance along the entire cycle that repeated in continuous rhythm. The right arms is now pulling. A complete cycle of both arms is completed as the left arm enters and the right one begins the power phase (Figura1.17.j).

Looking at the swimmer from the front view throughout the stroke, the posture of arm, elbow and hand change continuously because of theese movements let the swimmer reach and apply muscolar power(Figura1.18).
The arm stroke moved between pull and push phases. The hand goes underwater pushing down fingertips first, and the elbow is higher than the hand. The entry is on an imaginary line forward of the armpit and the arm reach the full extension. Later the hand moves backward, and elbow, progressively, get an approximately 90 degrees flexion. During the pull phase, the elbow is higher than the hand and pointed sideways in what we call elbow-up position. With this body configuration the swimmer can reach maximum leverage and reduces water slipping off the hand. The stroke ends with arm not completely extended. The rotation of the body implies that hand and forearm move laterally inward and outward under the torso. In this way we have a production of a natural sculling effect.

The arm is relaxed to enable the momentum created during the stroke to carry the arm into the recovery with minimal muscular effort. It's important for the athlete to perform the movement slowly, although it is composed by a sequence of different movements. A complete fluency is achieved when a swimmer can repeat correct pattern for stroke after stroke.

In Figura1.19 we can observe the right movement for a crawl start.

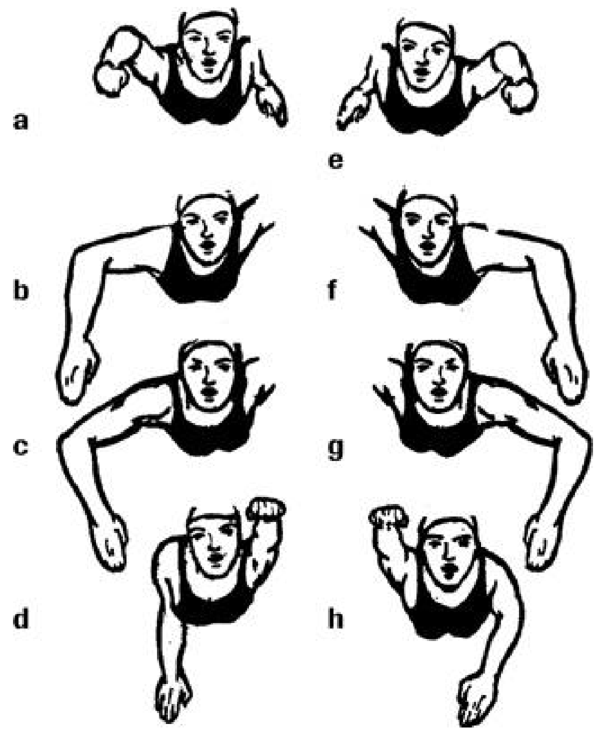

Figura 1.18: Crawl: front view.

At the beginning of the movement the feet are positioned with toes gripping the front of the block. The hands grasp the block with one hand on either side of feet. When the competition start, the swimmer pulls the body downward until the heels lift to tip the swimmer's barycenter forward over the front of the block (Figura1.19.b). The arms are thrown forward as the legs extend vigorously (Figura1.19.c) and the swimmer's body is fully extended as it reaches the peak of its trajectory (Figura1.19.d). As the head tucks down below the arms, the hips are piked to help swimmer achieve an ideal angle of entry (Figura1.19.e and Figura1.19.f). The entire body enters through the same hole in water and, as soon as the body is completely submerged, the swimmer arches the back to bring the body horizontal to the surface (Figura1.19.g).

Many swimmers moves with a dolphin kick before starting the flutter kick prior to surfacing (Figura1.19.h andFigura1.19.i). The first arm stroke brings the swimmer to the surface, while the other arm remains extended forward (Figura1.19.j and Figura1.19.k). As soon as the head breaks the surface, both arms take up the rhythm of the full stroke (Figura1.19.l). No

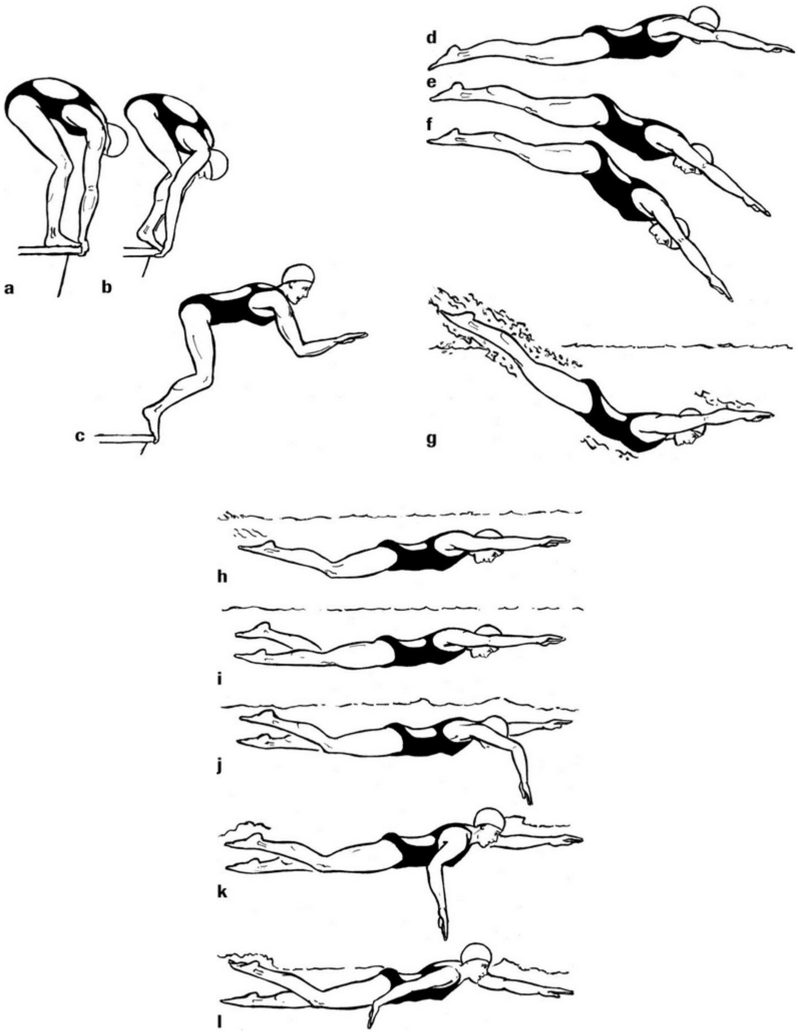

Figura 1.19: Crawl start.

matter what distance is being swum, the swimmers should not turn the head to breathe until he or she has taken about six strokes after surfacing well into the stroke rhythm.

The rules restrict swimmer to 15 meters underwater after the start and turn. At this point, the head should appear above the surface.

The crawl's turn consists of a forward somersault with a half-twist. The swimmer's forward momentum is first arrested and then developed in the opposite direction. If the head stop at any stage of turn, momentum is lost, and so is speed.

On the approach to the wall, the swimmer uses incoming forward momentum to provide the initial rotating movement of the turn 1.20.a.

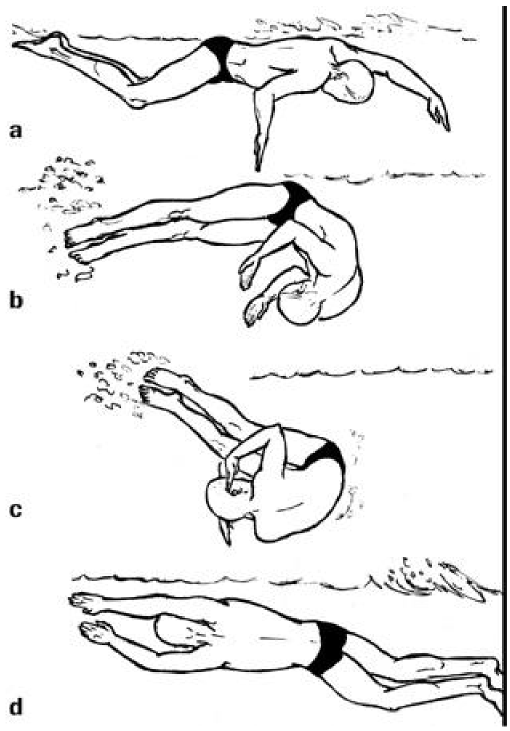

Figura 1.20: Crawl turn.

The head and forward arm are submerged under the surface and a quick dolphin kick adds momentum and lifts the hips. The whole body moves continuously. The back is brought toward the wall as the high hips and the knees are carried into the chest. When the wall is achieved, the forward hand continues his movement. In the meantime the pulling arm ends a half stroke and flexes at the elbow to join in a backward sculling motion with the forward arm, which is also now bent.

Meanwhile turn is being completed, the body performs a half twist (1.20.c). As the hips pass over the head, this one continues through and feet are placed on the wall. It is not required that the hands touch the wall, but that some part of the body touches the wall. Later the leg thrust begins: using the toes swimmers pull the wall. Simultaneously, the arms extend forward and the swimmer obtains a prone position. Now the body should be deep so that it prevent to go into disturbed surface water. Rules limit the underwater phase at a maximum distance of 15 meters: after that length head has to be emerged.As the swimmer planes gradually to the surface before taking the first stroke (Figura1.20.d), the athlete can use either a dolphin or a flutter kick. Six strokes should be taken before the swimmer resumes a regular breathing pattern.

1.2.2 Backstroke

The technique of the back crawl stroke is, for many aspects, similar to the front crawl. However we can cite two important differences:

- The position of the head: face is not submerged so there's no need for head turning inhaling mechanism;
- The stroke is not performed with arms out to the side of the body;

The pull in this style is less efficient than in the crawl style because arms are in mechanical disadvantage when they cannot pull directly under the body developing their full potential power. Analyzing this technique from a side view (Figura1.21) we can observe that the right arm has entered the water a split-second before the left arm has completed its stroke so that is guaranteed a continuous propulsion. The right elbow is flexed when as soon as the arm starts its pull phase (Figura1.21.b). The roll of body toward the pulling arm gives let the trunk muscles begin their action. The left arm, with the shoulder leading, is about to leave the water.
The right elbow bend start to increase as the left arm recovers in the vertical plane (Figura1.21.c). The head is centered in the long axis of the body so that it ensures a perfect balance and prevents the hand from breaking out of water. The right hand and forearm are at an approximately 90 degree angle to the surface. The left hand moves slightly faster than the right, ensuring the necessary slight overlap in the timing of arms. The recovery arm, still in the vertical plane, accelerates as it reaches forward to the entry (Figura1.21.e). The hand will enter little finger first. The right hand and forearm, nearing the end of the push phase of stroke, accelerate rapidly. The upper right arm is drawn toward the swimmer's side as the elbow extends, and the hand, relaxed at the wrist, thrusts directly backward. The left arm enters the water (Figura1.21.f), and the slit second timing of the arm is repeated, giving the stroke perfect symmetry. The left arm goes deeper in

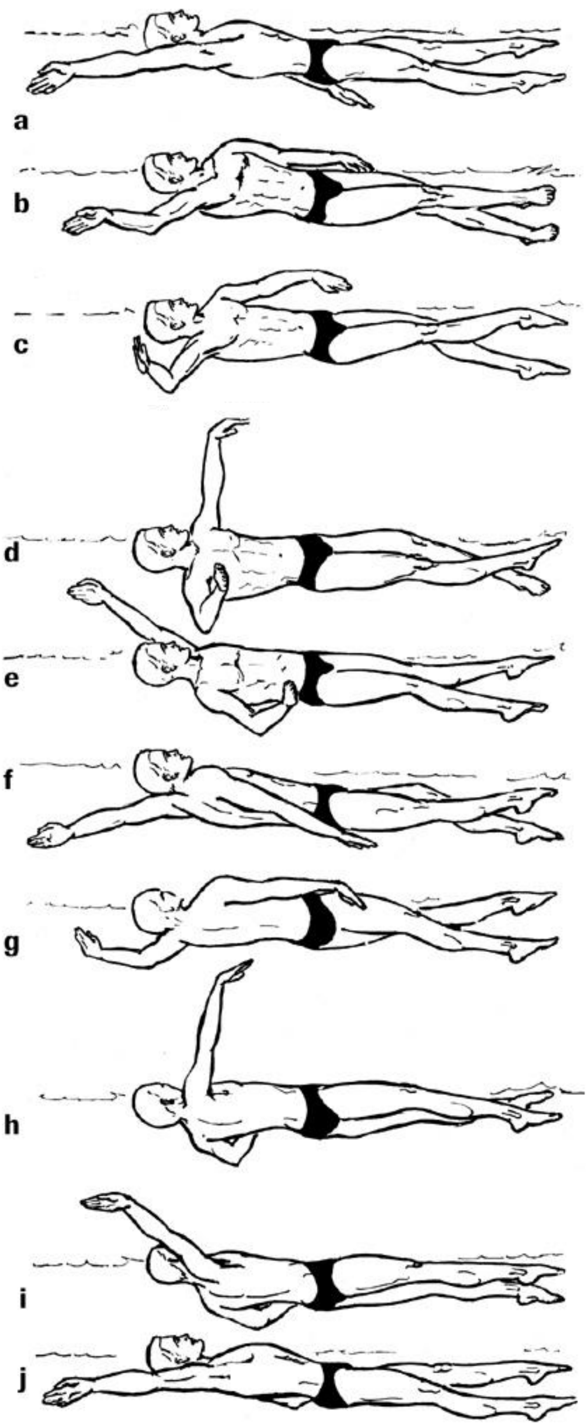

Figura 1.21: Backstroke: side view.

line with the back, so that the hips are brought higher and the resistance is reduced. The hand, palm down, finishes the stroke pressing down below the hip. With the shoulder leading, the right arm moves smoothly into the recovery without waiting at the hips(Figura1.21.g). The body roll brings trunk muscles into play and allows the swimmer to synchronize the pull of the left arm with the vertical recovery of the right arm (Figura1.21.h). The right arm, still recovering vertically, moves to the entry slightly faster than the left hand, which is completing its stroke (Figura1.21.i). Finally the cycle is completed.

From a front view, the arm submerged behind the shoulder, elbow straight, little finger first (Figura1.22.a).

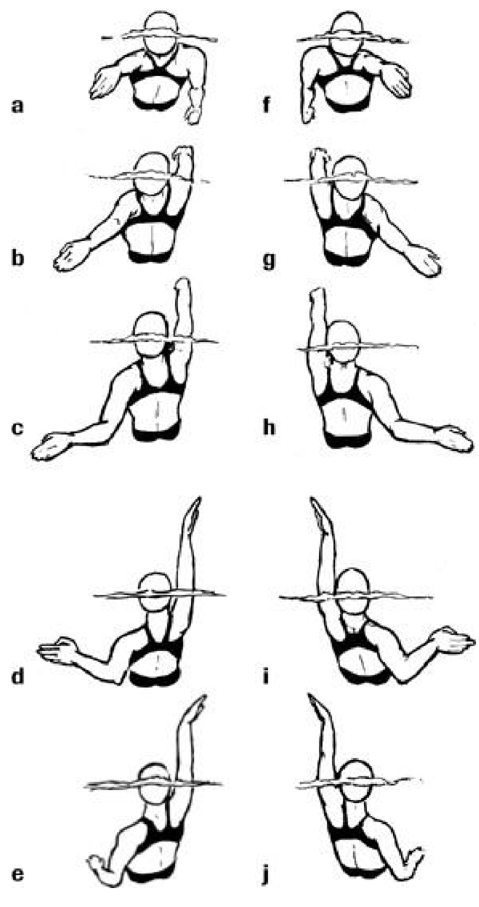

Figura 1.22: Backcrawl: front view.

The other arm, palm down, completes its pull with a vigorous thrust below the hip. For only a few seconds, both arms are completely submerged ensuring continuous propulsion. Without pausing, the entry arm presses down deep to a line with the back. Then the elbow starts to be flexed and the body rolls towards the pulling arm (Figura1.22.b). The other arm, with elbow straight, recovers in the vertical plane in a trajectory aimed directly over the shoulder. The body roll starts to reverse direction. The elbow of the pulling arm continues to bend to a maximum of 90 degrees (Figura1.22.d). The recovery arm, without deviation from the vertival, accelerates slightly as it passes back over the shoulder (Figura1.22.e). This acceleration will cause a slight overlap in the stroke as the arm enters the water. The pulling arm with the upper arm drawn to the side of the body is now set to thrust backward to the end of the stroke (Figura1.22.fand Figura1.22.j). The same sequence of pull and recovery is repeated on the other side of the body.

At the beginning of a race, the swimmer (Figura1.23) holds steady by gripping the handles and placing one foot below the other against the wall. This is made to avoid slipping.

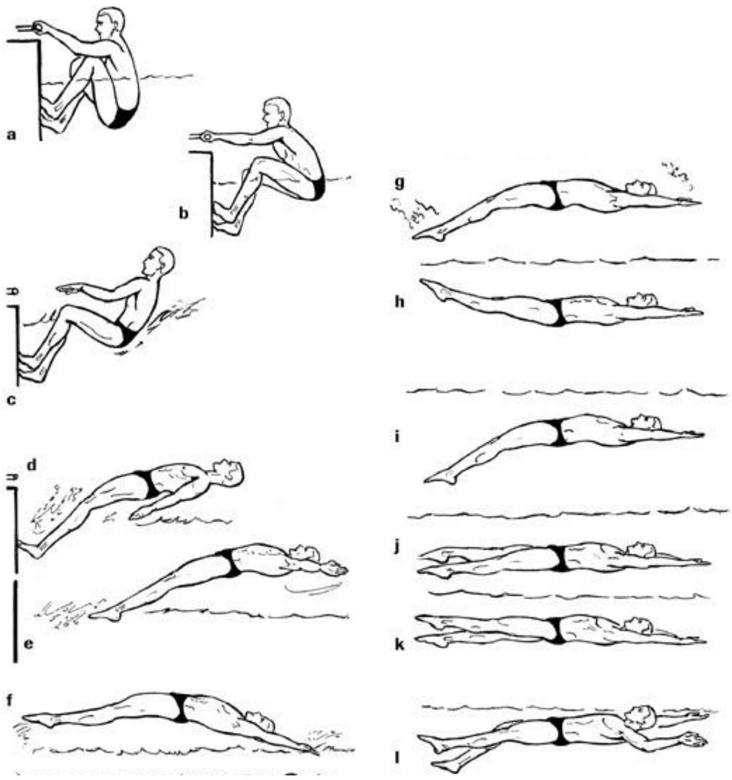

Figura 1.23: Backstroke: the start.

With the generation of pressure at fingers and toes level, the swimmer is ready to start the race as a spring. The head is positioned in an erect way and the eyes are directed forward. When the race begins, the swimmer pulls strongly on the handles and pushes with legs. The hips lift and the swimmer starts to move out over the water. The head is aligned with the spine and a further momentum is added as feet and ankles extend to give a final powerful thrust against the wall. The arms are thrown vigorously out sideways and forward as the body launches into a shallow dive over the water(Figura1.23.e).The swimmers has not to land flat on the back because this would generate a big resistance(Figura1.23.f). The next step for the swimmer, before start kicking up and down, is to take a short glide with the arms fully extended and the head back between the arms to ensure good streamlining. A swimmer may do either a dolphin kick (Figura1.23.g,1.23.h and 1.23.i) or a flutter kick (1.23.j,1.23.k and 1.23.l), depending on individual aptitude. The underwater dolphin kick is faster than the full stroke on the surface because there's no wave drag underwater that is a considerable component of the overall drag in surface swimming. The swimmer commences the stroking action pulling with the strongest arm first, and he has to take care to keep the other arm submerged and well behind the head. The first stroke should be close to the body so that, in combination with the streamlined position of the submerged arm, will keep the swimmer moving straight during the breakout into the surface. It is recommended not to inhale for the first six strokes: in this way swimmers immediately work into a fast tempo instead of a gradual buildup to speed with each successive stroke.

In backstroke style when the swimmer approaches to the wall, looks toward the forward arm and starts to roll the entire body in the same direction. The athlete begins to turn his head when he is facing the bottom of the pool. In the meantime the forward arm does a reverse sculling motion that causes the shoulders and hips to roll over. The left arm and left leg cross over the body's long axis to assist the body's continuing roll to the prone position.
The head keeps moving as it leads the body into a forward somersault aided by a dolphin kick that lifts the hips as the body pikes, and the back is thrown over toward the wall. Both hands assist in pulling the body forward and over (Figura1.24.c and Figura1.24.d). Now the hands join together as they quickly reverse direction to help the body maintain its continuing roll (Figura1.24.e). The legs swing over the head, and the feet are placed lightly on the wall without the heels touching the wall (Figura1.24.f). Once again on the back, the swimmer pushes off with arms and legs extended and the entire body in a streamlined posture (Figura1.24.g). The swimmer will use either a dolphin kick or a flutter kick before starting the arm stroke. To complete a length, some part of the swimmer must touch the wall. During the turn shoulders may turn past the breast. If the swimmer turns past the vertical, such motion must be part of a continuous turning action and the swimmer must return to a position on the back before leave the wall[16].

[16]cfr. FINA rule on the backstroke turn

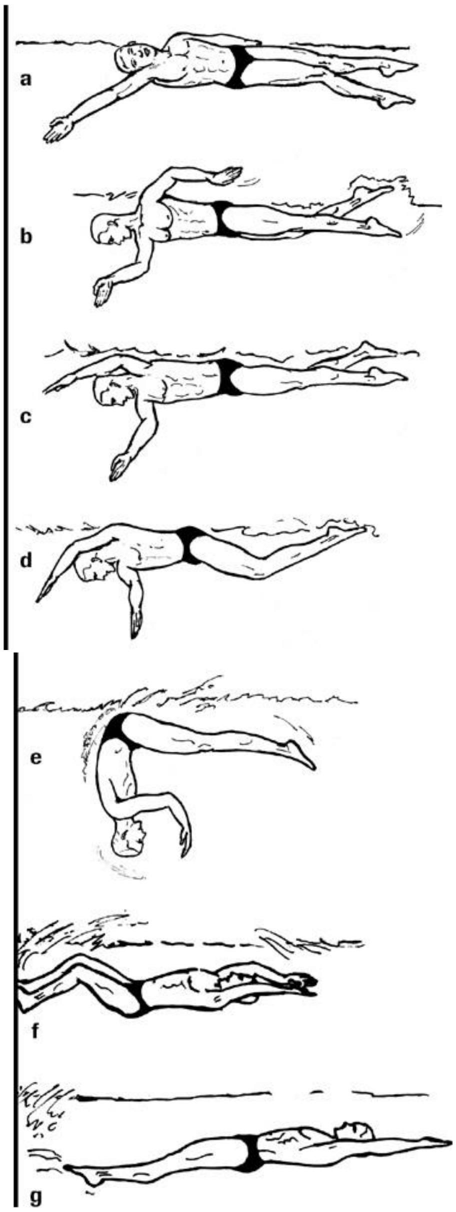

Figura 1.24: Backstroke turn.

1.2.3 Breaststroke

Looking at a swimmer from the side view (Figura1.25), we can observe the body in a streamlined posture with abdominal muscles drawn in and lower back flattened.

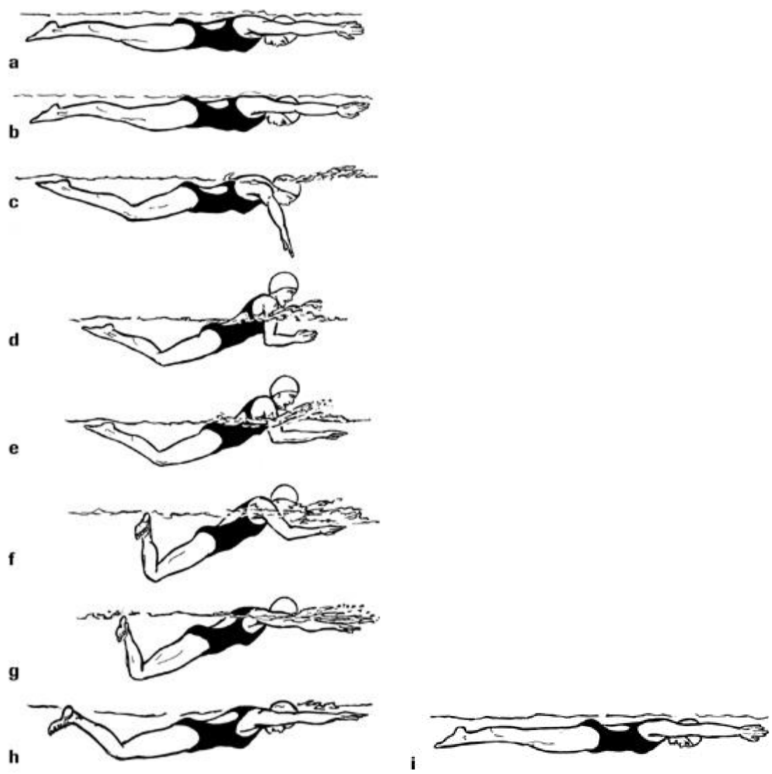

Figura 1.25: Breaststroke:side view.

Arms and legs are fully extended, and feet are pointed. The head is between arms, and the swimmer looks straight down at the bottom of the pool (Figura1.25.a). This position repeats when the stroke cycle ends (Figura1.25.i). Later palms turn outward as the hands plane slightly upward to meet the oncoming flow of water (Figura1.25.b). With elbow up and in line with the shoulders, the swimmer completes an initial circular motion, at the end of which the hands are planed directly backward (Figura1.25.c). The hand and forearms are ready to change direction: the swimmer focuses on pulling the body forward. The front thighs remain lined up with the body. The swimmer begins to hollow the back, thus preserving planing action of the body. streamlining is maintained as the heels lift gently and the knees spread slightly sideways. The head, shoulders, and front chest clear the surface (Figura1.25.d). With the upper body still clear of the surface, the swimmer concentrates on moving forward. The swimmer inhales as the mouth comes out the water. The hands sweep down under the shoulders and continue forward with forearms following. The feet do not hang down to cause resistance; both feet are kept in line with the shins. In this particular technique, called *wave action breaststroke*, the swimmer performs "*the lunge*" phase: this is a transition, between the pull and the kick, so that he can follow the wave. In other words, the hands and forearms are thrust forward on and parallel to the surface of the water and the swimmer throws the body forward over the water. The body continues to slide forward with back still curved. The front thighs are kept in line with the torso to permit a smooth passage of water under the body. The heels rise in preparation for the kick, which will start when the lunge is about three quarters through. The kick doesn't start the lunge but rather serves to maintain the lunge and keep the swimmer on the surface. The upper arms do not come close to the side of the chest but follow the hands in front of the chest to reduce frontal resistance (Figura1.25.f). The posture of the back quickly changes from its arched concave shape to an exactly opposite rounded convex shape. As the kick starts, the degree of hip-joint flexion is approximately 35 degrees, with the lower leg at almost 90 degrees to the surface. The feet, close below the surface, are dorsi-flexef (everted, or turned outward) at approximately 90 degrees to the shin to catch the water efficiently. Lowering the hips slightly helps the swimmer accomodate this changing posture of legs, thighs and torso. The humped dolphin like posture of the back and a powerful, directly backward kick help the swimmer keep moving over the water with shoulders and arms at the surface (Figura1.25.g). The feet remain everted until just before the kick closes, at which point the ankles and feet extend to provide a final snap to the kick that thrust the water directly backward (Figura1.25.h). The swimmer maintains streamlining by looking at the bottom of the pool during this powerful phase of the overall action. The swimmer slides forward under the surface with body in streamlined alignment (Figura1.25.i). The swimmer must not let the legs drop, as a judge may consider this a dolphin kick and can disqualified the swimmer.

Considering the front view, as we can see in figure Figura1.26, the body glides forward as far as possible, and the upper arms press against the ears to further streamline the oncoming flow of water along the body. In the first stage of the arm pull, the elbow bend continues as the hands sweep down and inward (Figura1.26.d).

Elbows are kept away from the side trunk as the hands join. The head, shoulders and front chest emerge from water as the swimmer inhales Figura1.26.e. Later the swimmer starts the forward "lunge" of the arms shown in Figura1.26: the kick is directly backward and occurs three quarters into the lunge, helping the swimmer maintain the momentum of the lunge. The head is down as te legs close to complete their backward thrust. Arms and shoulders reach

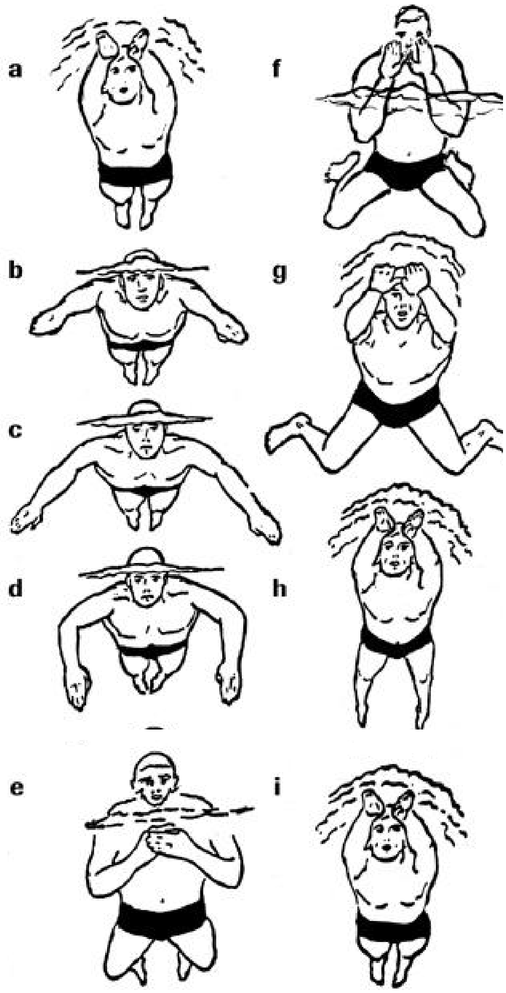

Figura 1.26: Breaststroke:front view.

forward as far as possible Figura1.26.h and with arms and legs outstreched, the body, once more submerged in streamlined alignment, slides forward parallel to the surface (Figura1.26.i).

The start, shown in Figura1.27 in breaststroke style, is characterized by feet positioned with toes gripping the front of the block.

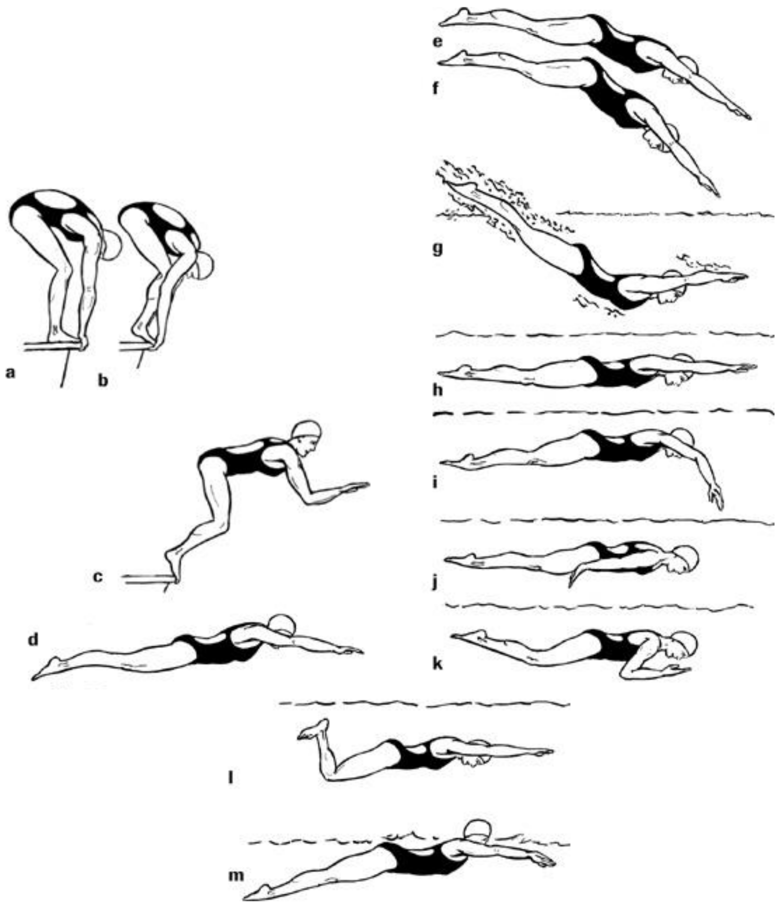

Figura 1.27: Breaststroke start.

The hands lightly grasp the blockwith one hand no either side of the feet (Figura1.27.a). At the starting signal, the swimmer pulls the body downward until the heels lift to tip the swimmer's center of balance forward over the front of the block (Figura1.27.b). The arms are thrown forward as legs extend vigorously (Figura1.27.c). The swimmer's body is fully extended as it reaches the peak of its trajectory (Figura1.27.d). As the head tucks down below arms, the swimmer pikes at the hips to achieve a steep entry with the entire body plunging through the same hole in the water (Figura1.27.e and Figura1.27.f). The lower back is arched to keep the body moving directly forward and parallel to the surface (Figura1.27.g). The underwater swimming phase, after start or turn, begins with a short preliminary glide with body outstretched and streamlined (Figura1.27.h). Then follows a long pull through to the hips with another short glide with the arms close to the body (Figura1.27.i and Figura1.27.j). The hands are turned palms up as the arms, with elbows and forearms kept close to the body in streamlined fashion, are extended forward (Figura1.27.k). As the legs kick, the back of the head is tucked down in line with the upper surface of the arms to ensure good streamlining (Figura1.27.m). After a start or turn, rules permit a swimmer to take one stroke completely back to the legs and one kick while wholly submerged. The head must break the surface of the water before the hands turn inward at the widest part of the second stroke.

The breaststroke turn follows the indications of FINA rules. Both hands must touch simultaneously at, above, or below the water's surface(Once the swimmer touch the wall, shoulders must be at or past the vertical toward the breast. The swimmer use the body's momentum to bring the body in toward the wall. Then, by keeping head and shoulders moving out again, redirects the momentum in the opposite direction. The swimmer allows momentum to bring the body in toward the wall. At the touch the swimmer should not allow the body to come too close to the wall (Figura1.28.a). After touching the wall, arm, on the side to which the body will turn, is pulled back from the wall with elbow bent (Figura1.28.b). The opposite hand pushes against the wall to move swimmer's head and shoulders away from the wall (Figura1.28.c). As this happens, knees are bent and tucked under the body. During this motion, swimmer inhales in preparation for the pushoff and ensuing underwater swim. The touching hand is removed frome the wall and joins with the free hand to prepare for the outward thrust from the wall. Note the sculling motion of the right hand, which increases the speed of the body's rotation and helps set the swimmer at an ideal depth below the surface. Feet are placed on the wall, the swimmer thrusts out into the pushoff with body streamlined and arms and legs extended (Figura1.28.d). In the pushoff from the wall, the body remains streamlined, with arms and legs extended and head beneath the arms and balanced evenly on the breast (Figura1.28.e). FINA rules state that after the start and each turn swimmer may take one arm stroke completely back to the legs and one leg kick while wholly submerged. The head must break the surface of water before hands turn inward at the widest part of the second stroke. Figura1.28).

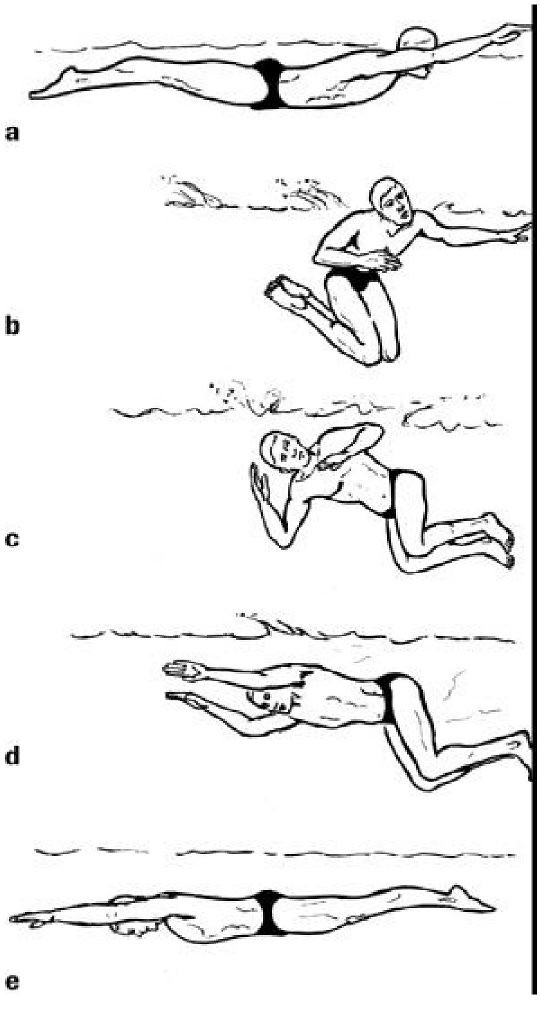

Figura 1.28: Breaststroke turn.

1.3 Biomechanics of Swim

1.3.1 Drag

It's easy to think how drag, in swimming, has a relevant role [47] [32]. When an athlete swim in water his body undergoes a retarding force due to resistance. Many different kinds of resistance can be developed during swim: this depends on the particular environment in which this movement is done. We can observe mainly three components of drag:

- Friction drag;
- Pressure drag;
- Wave drag.

Friction drag is a resistance's component due to the viscous property of water. In other words it leads to a frictional force between different layers of water as they move past one another. The viscosity of water is expressed by its coefficient of viscosity η equal to $0.89710^{-3}Nsm^{-2}$ for water at 26 Celsius. The adhesive forces held on the athlete's surface the water layers directly in contact with skin (no-slip condition) in this way this portion of fluid moves with the same speed as the swimmer. The further is the layer from the body the lower is the velocity. In this way the layer close to the body will be retarded by the nearest layer and this one will be retarded by the next one and so on. It has been found that this friction or viscous force is proportional to the total wetted surface of the swimmer and to the speed. As long as the water is arranged in layers, in what we call laminar flow, the total drag will equal this viscous force. But, above a certain speed, the flow become turbulent so that we have a chaotic movement of fluid elements. The onset of turbulence occurs at a critical values called Reynolds number (Re): this is a dimensionless number and depends on shape and size of swimmer. In particular:

$$Re = \frac{vL\rho}{\eta}$$

where ρ and η are the density and viscosity of water, v is the swimming velocity, and L is a characteristic length of the swimmer. For a competitive swimmer, with $v = 2ms^{-1}$, $L = 2m$, $\rho = 1000kgm^{-3}$ and $\eta = 0.89710^{-3}Nsm^{-2}$, the Re value is about 4.510^{6} for the swimmer body. If we think that, given the shape of an object, the critical value of Re will be in the order of 500000 [34], we conclude that in competitive swimming turbulence always plays a role.

During the swimming, at a certain point, the orderly flow may separate depending on shape, size and velocity of the athlete. At this point the flow reverses and may roll up into distinct eddies. In this way a pressure differential is created between the front and the rear of the swimmer thus creating a *Pressure drag* proportional to the pressure differential times the cross sectional area of the swimmer. From a mathematical point of view we can describe the pressure drag as:

$$D_p = \frac{1}{2}\rho A_p v^2 C_D$$

where v is the speed, C_d is a dimensionless drag coefficient accounting for form, A_p is the cross sectional area and ρ the density of water.

The *Wave Making Resistance* occurs when the athlete swims near the surface. In this situation water tends to pile up in front of the swimmer and to form hollows behind creating a wave system. When the velocity increases we have also an increasing of both the wave length, defined as crest to crest distance, and the wave amplitude. As soon as speed arrives at a certain value the wave length becomes equal to the water line length of the swimmer which is presumably proportional to the height of the swimmer. This value is the so called *hull speed*, a term from shipbuilding introduced into competitive swimming by Miller. When the athlete swims at that velocity he is trapped in a self created hollow between crests of waves. In this condition more effort will lead to a higher wave amplitude leading to a deeper hollow so that any other attempts to increase swimming speed won't help the athlete because the energy is used to climb out of the hollows [16]. In other words we can say that it is impossible to swim faster than the hull speed. From a theoric point of view the wave drag is influenced by two factors: the first one is the form of swimmer the second is the relative speed. This two components are summarized in what we call Froude-Number (Fr) which is a dimensionless number given by:

$$Fr = \frac{v}{\sqrt{gL}}$$

In this formula v is the speed, L is a characteristic length of the swimmer and g is the acceleration of free fall ($9.81ms^{-2}$).

In this issue we have to consider also that the movement necessary to create propulsion could induce additional resistance. Many works [41] [35] [36] tented to determine the drag of an active swimming person. Finally it seems that there is a relationship between the active drag with the square of the swimming velocity according to the following equation:

$$D = Kv^2$$

We can also affirm that the total drag can be theorize with the sum of its three component:

$$D = D_p + D_f + D_w$$

Pressure drag is dominant at the prevailing high Reynold's number (Re of $2.210^6 - 2.510^6$) and at equal swimming speed is determined mainly by the body cross sectional area.

Friction drag D_f, being dependent on total surface area, could increase somewhat since the total skin surface will increase due to growth.

Wave making resistance relates to the Froude number that considers the increase in height. Thus swimming at the same absolute speed would imply, during growth, a decrease of Froude number and consequently a lower wave making resistance. This is the reason why we can suppose that for a shorter swimmer a higher Froude number corresponds to a lower velocity than an higher one so that a taller swimmer seem to have an advantage for a good swimming performance.

We can observe also that during growth the changes in height, body shape and body cross sectional area could affect the performance of a swimmer with opposite effects on drag.

Another interesting issue is that proposed by Vorontsov **??** in which he explains how, at a certain depth, wave making resistance would be negligible. He starts from consider that, during an immersion,swimmer can gain a certain depth in which the hydrostatic pressure is higher than the pressure created by the moving swimmer that sets up a wave system. This *wave equilibrium depth* appears to be between 0.7 and 1.2 m. Vorontsov stated, in his work, that the water making resistance is related to the swimming velocity cubed so that it's simple to understand that this component rises sharply and becomes significant at high speeds. These magnitudes can be approached by the swimmer in, mainly, two phases: the turn and the start. So a glide below the wave equilibrium depth would evade this high wave making resistance, and thus a much smaller propulsive force is required to maintain high speed. This means that athletes have a performance advantage when swimmer under and, in this way, they can achieve a high swimming speed.

From what we've said before, we can conclude that drag is also affected by anthropometric dimensions:there are several methods to obtain a small decrease in drag like that of stretching the arm in glide phase or stretching the shoulders behind the arms. Furthermore we can observe how trained swimmers are able to synchronize the propulsive peaks with the phase in which the body cross sectional area, and thus the pressure drag, is at maximum so that the resultant force on the swimmer shows much less variations.

1.3.2 Propulsion in swimming

When a swimmer moves his hand backward, the drag forces generated would propel swimmer forward. This is a direct consequence of the Newton's third law (action and reaction forces). This push of the hand is not obtain with a straight movement of the hand but following a curvilinear path (Figura1.29).

In the propulsion generation mechanism also lift forces have a relevant role. They act perpendicular to the direction of movement and their nature

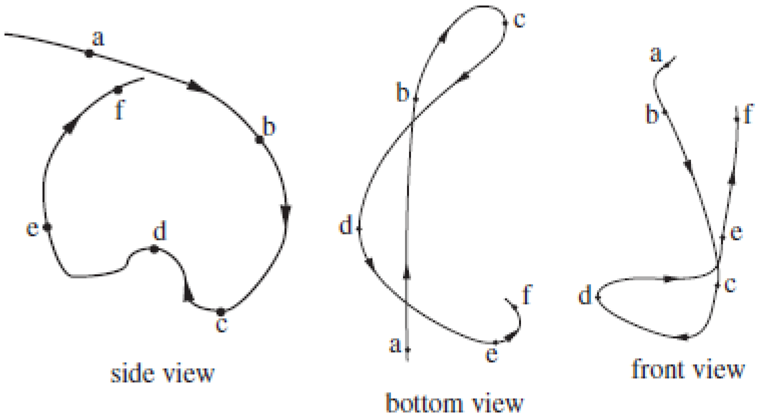

Figura 1.29: Front crawl stroke pattern of the right hand in three dimensions. $a-b$: entry, $b-c$: entry scull, $c-d$: inward pull or insweep, $d-e$ outward pull, $e-f$: exit or upsweep

are similar to that experienced by an aircraft wing. Indeed, with its curved surface, a wing provides aerodynamic lift because the upper surface it sharper than the lower one so that the air moving over the top surface is focused to move more quickly. In this way we have the creation of a lower pressure on the upper surface as compared with the lower surface and this results in aerodynamic lift (Bernoulli's Principle). The lift force is directed at right angles to the line of motion of the propelling surface(Figura1.30). According to hydrodynamic theory the drag and lift force can be derived

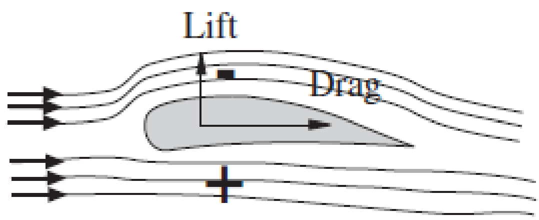

Figura 1.30: Lift and Drag action during swim.

using the following equations:

$$L = \frac{1}{2}\rho u_h^2 C_l S$$

$$D = \frac{1}{2}\rho u_h^2 C_d S$$

where L is the lift force, D the drag force, ρ the density of water, u_h the hand velocity, C_l the lift coefficient, C_d the drag coefficient and S the propelling surface of the hand. $C_l and C_d$ are functions of the angle of attack and sweep back angle and they were determined in a fluid lab using hand models [46]. The *angle of attack* is the angle formed by inclination of the propelling surface to its direction of motion and the *sweep back angle* defines the leading edge of the hand (Figura1.31). These coefficients are strongly dependent on

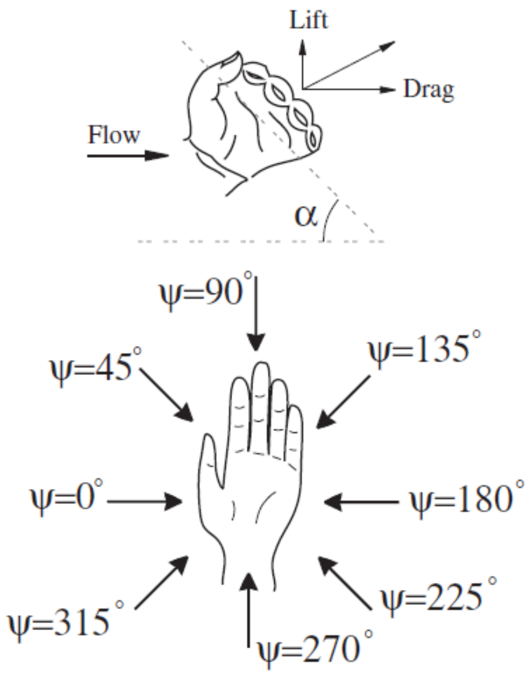

Figura 1.31: The angle of attack α and the sweep back angle Psi

the angle of attack: small changes in the value of the angle can cause huge variations in the resulting propelling force (vector product of lift and draf forces). Thus the propelling force can be steered in the desired direction by varying lift and drag forces components trough a modification of the angle of attack. In order to select the best angle of attack at every moment of a pull, swimmers have to have a *feel of water*. Swimmers usually use complex sculling motions of the hands and the most rapid hand action (high velocitie v, implying high propulsive forces) in the side-to-side and up-and-down dimensions of motion, rather than in the front-to-back direction.

In addition we cannot consider negligible that the water is under the unsteady flow condition and this brings us to consider also two important dynamic effects associated with an immersed accelerating segment: vortex shedding and dynamic stall. Comparing the hand movement to that of a wing, we can affirm how the total airflow around wing may be decomposed

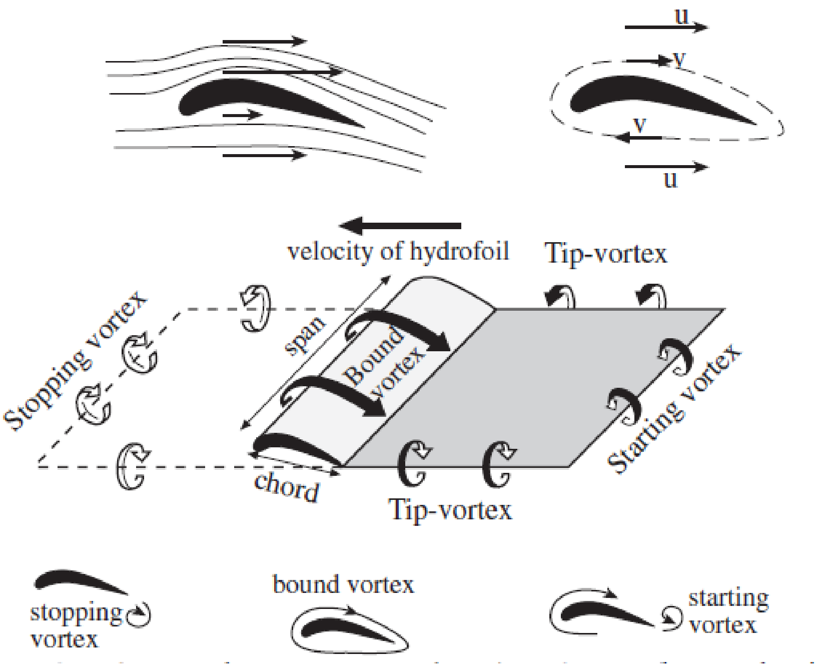

Figura 1.32: Streamlines round an wing, which is shown in section. The flow past the wing can be decomposed in uniform flow with velocity u with a circulation around the wing with velocity v. The $3-D$ vortex wake created by a rapid acceleration of a wing is shown at the top. The shaded area indicates air given a downward impulse. Dashed lines and unshaded vortex indicate future events. Creation of the starting, bound and stopping vortices is shown below in a $2-D$ view, depicting the vertical plane.

in a circulating flow around the wing with velocity v and a uniform flow at velocity u passing the wing (Figura1.32). The velocity of the air above the wing wil be $u+v$, and beneath it $u-v$. The pressure difference can be appsoximated by:

$$\frac{\rho(u+v)^2}{2} - \frac{\rho(u-v)^2}{2} = 2\rho uv$$

This pressure difference acting across a wing of area A_p, gives a lift force of $2\rho uvA_p$. The circulating flow around the wing is called a *bound vortex*.The strength or *circulation* of the bound vortex is proportional to v. In this case we can approximate circulation with the circumference of the wing (twice the chord c) multiplied by v, hence:

$$\Gamma = 2cv$$

The lift on a wing of span s with circulation Γ must be equal to that calculated before and is given by:

$$L = \rho u \Gamma s = \frac{1}{2}\rho u^2 C_l c s = \frac{1}{2}\rho u^2 C_l S$$

Circulation and lift are constant for a wing moving at a constant speed (steady state). However when the wing accelerates impulsively from rest to a certain speed, the circulation needs time to build up. At the start air swirls around the trailing edge and vortices are shed into the wake: this mechanism continues till a constant circulation is reached. This gradual build up of the bound vortex is the so called *Wagner effect*. Even after six chord lengths of travel the circulation and lift are only 90% of the final value. Since the chord of a hand is about 0.1 m, the steady state value of circulation (requiring > 0.6 m of travel a constant velocity) may not be reached at all during swimming.

A fundamental rule of fluid dynamics is that no vortex can be created unless a vortex of the opposite sense and strength is set up simultaneously (Kelvin's circulation theorem). Thus the starting vortex is equal in magnitude but opposite in sense of rotation to the bound vortex. They are created as air swirls around the tips from the higher pressure zone below the wing to the lower pressure zone above. Accidental entrapment of air in the water often produces visible evidence of tip vortices trailing behind a swimmer's hand in the early stages of the stroke. Thus the hand generates a vortex ring, enclosing water that has been blown downwards. When the hand motion stops the bound vortex then swirls off the trailing edge and forms the stopping vortex, closing the vortex ring, which subsequently moves backward. Whether the water flow associated with swimming propulsion is unsteady or quasi-steady, the reaction force to the lift must impact momentum to the fluid. With a periodic propulsion, as in swimming, the formation of start-, tip- and stop-vortices is unavoidable. This may well result in a vortex ring left behind in the wake during each half-stroke: the momentum of this ring must correspond to the lift force generated during the half-stroke.

The lift coefficient of a wing, and thus of the hand, is proportional to the angle of attack, up to a certain limit due to a phenomenon called *stalling*. The angle at which stalling occurs is called *stalling angle*. When the angle of attack is less than this value, the flow is attached to the surface of the wing. When it is greater than the stalling angle, the flow separates from the upper surface of the wing and large eddies form leading to a sudden drop in lift force and hence of $C_l(\alpha)$.

Circulation and lift will not grow to steady state values on each half stroke, thus the quasi-steady estimate of lift is overly optimistic, and the discrepancy with actual forces produced is even greater. So there are mechanisms of lift enhancing that can due to a rotation of hands like that used by swimmer in front crawl style during the transition from insweep to outward pull. So we have to focus on other kind of unsteady mechanisms to explain propulsion in swimming.

We have said that if the angle of attack increased above the stalling angle, suddenly we have the separation of flow. However if the angle of attack is suddenly increase above the critic value, separation of flow is delayed and the wing may move for several chords generating lift that exceeds the maximum steady state value. The growth of lift beyond the values observed during steady state are associated with the formation of a leading edge vortex. This vortex is created when the flow separates from the wing at the onset of stalling. As long as the leading edge vortex is above the wing, circulation around the wing is enhanced, leading to significantly increased lift forces. However the problem is that the leading edge vortex breaks away rather quickly and lift will reduce sharply because is a rather unstable phenomenon. Some experiments made using a scaled robotic model, showed that a strong leading-edge vortex was present during the down stroke, which was stabilized by a strong axial flow [27]. Thus in a flapping wing which rotates around the shoulder, the leading edge vortex was stable enough to remain attached along the wing until three quarters of the wing length during most of the downstroke. At the tip it separates and blends into a wide, tangled tip vortex. The leading edge vortex is stabilized by a strong axial flow, originating from a pressure differential that is caused by the velocity gradient between wing base, that moves faster, and wing tip. The velocity gradient is due to the rotation of the wing base about its shoulder joint, such that the up- and down velocity at the base is small but increase towards the tip. In the front crawl stroke a similar situation occurs 'cause the velocity of the hand relative to the water is higher than the velocity of elbow. This new mechanism seems to explain the high lift forces produced during movement and shows that the quasi-steady approach failed because:

1. dynamic stall cannot occur in quasi steady condition;
2. the crucial axial flow component is ignored in the quasi steady approach.

In conclusion, this hypothesis has to be confirmed by other studies but seems to well explain the complex dynamic of the propulsion in swim.

1.3.3 Energetics in swimming

At this point it is important to introduce another elements of utmost importance: energetics in swimming. Indeed in swimming the aerobic and anaerobic capacities co-determine success.

The oxygen uptake is directly related to the intensity of the effort as long as the swimmer is performing in steady state and at less than $50-70\%$ of the maximum oxygen uptake ($\dot{V}O_{2max}$). From different studies it was found that women require a ±30% lower rate of energy production than men to maintain a given velocity [45][44][33][23][43][40][42][24]. It was suggested that women didn't need to expend as much energy in staying afloat because of their higher percentage of fatty tissue. Furthermore the distribution of adipose tissue along the head-feet axis is more favorable in women than in men, so that the tendency for the feet to sink is lower. Thus women may need less energy to keep the body in a horizontal position, while it is also likely that a more horizontal position reduces drag.

During constant speed swimming a considerable fraction of the energy expenditure is utilized to overcome drag. The power to overcome drag(P_d) is related to the velocity cubed and a drag factor K according to:

$$P_d = Kv^3$$

It may be possible that the lower drag values for women is related to the difference in frontal area. Nevertheless the relationship between buoyancy, drag and energy expenditure remains to be determined.

We have, from an energetic point of view, to consider also that in an aquatic environment propulsion is generated by accelerating water. This acceleration can't be ignored: by Newton's Second law of motion, the forxe F required to give a mass m an acceleration $\frac{du}{dt}$ is given by:

$$F = m \bullet \frac{du}{dt}$$

So the force applied to the mass of water equals the rate of change of momentum ($momentum = mv$). The thrust, in this way, propels the swimmer forward generating a momentum by pushing water backward (Figura1.33). Suppose a swimmer obtains the thrust F required to swim with velocity v, by giving some of the water a backward velocity $-u$. Thus a mass of fluid will acquire a change of momentum and consequently the kinetic energy given to the water in unit time equals the force acting on the mass of water F times the velocity (u). This is the power consumed (P_k) in driving water backwards, in giving it a kinetic energy change, which is wasted power. Suppose that a swimmer swims at constant speed: in this case the resistive force will equal the propulsive forces. The power required to drive the swimmer through the water equals $F \bullet v$. This can be denoted as usefullpower and we can define an efficiency, known as the *Froude efficiency*, or propelling efficiency (e_p):

$$propelling\ efficiency = e_p = \frac{useful\ power}{useful\ power + power\ lost\ to\ water} = \frac{v}{v+u}$$

From this equation, since u will not be much smaller than v, follows that the generation of propulsion in a fluid always leads to the loss of mechanical energy of the swimmer that will be transferred in the form of kinetic energy to the fluid. Two aspects of this analysis are important for human swimming:

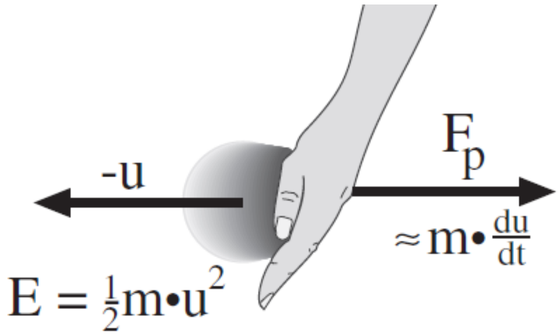

Figura 1.33: The propelling force F_p is generated by giving a mass of water m a velocity change $\frac{du}{dt}$. Consequently, the pushed away mass of water acquires a kinetic energ that is the result of the work done by the athlete. Hence part of the total mechanical work of the swimmer delivers is converted into kinetic energy of water, rather than forward speed of swimmer.

- the power losses are considerable ($e_p << 100\%$);
- the power losses to the water are highly dependent on technique.

The magnitude of the propelling efficiency depends on the propulsion mechanism: the efficiency is higher if the swimmer accelerates a large mass of water per unit time to a low velocity than by accelerating a small mass to a high velocity (see the previous equation). Consequently maximal swimming speed can be achieved by a swimming technique where optimal propelling force is obtained with an optimal propelling efficiency and a minimal body drag. Otherwise we can affirm how thrust and loss of mechanical energy are two sides of one coin: for the analysis of swimming mechanic we have to consider both aspects.

Propulsive force is created by the arms and legs of a swimmer as they push the water backwards. So some part of chemical energy may be transformed into kinetic energy of water.

The total mechanical work produced by a swimmer is spent in part to overcome drag and in part to generate propulsion. In swimming competition what is important is that swimmer has to optimize the swimming velocity so it is important to look at the time derivative of the work produced by the swimmer, in other words the mechanical power production. Power is defined as the rate at which energy is transferred from a system to another one, in this particular case from swimmer to the acquatic environment. It equals the dot-product of the force vector $\mathbf{F}$ and the velocity of the application point $\mathbf{v}$:

$$P = \mathbf{F} \bullet \mathbf{v}$$

Where **F** is drag propulsion and **v** is the swimming or hand velocity. The free body diagram shown in Figura1.34 underlines two major power components (ignoring gravity and the buoyant force): power necessary to overcome drag P_d and power expended in giving a kinetic energy change to pushed-away mass of water P_k. The mechanical power required to overcome drag will

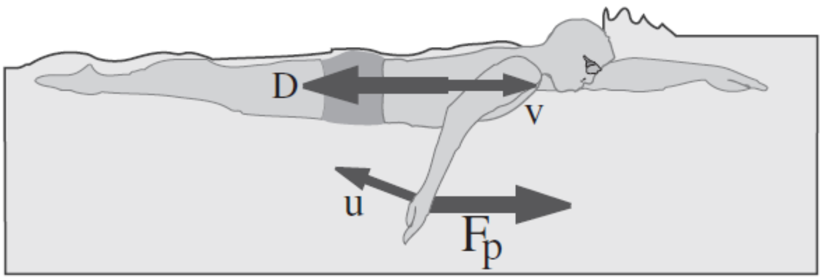

Figura 1.34: Free body diagram of swimmer: when swimming at constant speed, propulsion equals drag. Thus two major forces act on the swimmer in swimming direction, whereby the point of application of each force has a velocity. Since power equals the dot product of **F** and **v**, the diagram shows that one energy flow relates to drag and one to propulsion

.

thus equal:

$$P_d = \mathbf{D} \bullet \mathbf{v} = Kv^2 v = Kv^3$$

The mechanical power lost in the generation of propulsion (P_k) is less obvious to calculate. It is possible to use one of this three methods:

1. Estimate the transfer of kinetic energy to the water on the basis of measured kinematics and estimated kinetics of the propelling surfaces, whereby the propelling force ($\mathbf{F_p}$) and its velocity **u** are estimated so:

$$P_k = \mathbf{F_p} \bullet \mathbf{u}$$

2. Quantify the rate of kinetic energy change of the water;

3. Estimate the difference in rate of total energy expenditure between swimming whereby the push-off is made against water, and swimming whereby the push-off is made against a fixed point (in this case $P_k = 0$).

In the last technique, the difference in rate of energy expenditure, when swimming at the same velocity, is proportional to P_k. The magnitude of P_k is estimated by multiplying the difference in rate of energy expenditure ($\dot{E}$) with the gross efficiency. In this way we can calculate the propelling efficiency as:

$$e_p = \frac{P_d}{P_o} = \frac{P_d}{P_d + P_k}$$

In highly trained swimmers were found values of e_p of 61% [48] whereas in triathletes (not skilled swimmers) this value becomes 44% [31] underlying the importance of technique in the optimization of propelling efficiency.

The propulsive force is caused by momentum flow convected by vortex action. The circulation Γ of the wake vortex is determined as the rotation velocity (ω) times the radius of the vortex. From a three-dimensional point of view, the center of a vortex forms a line and the strength of a vortex line is constant along its length. A vortex line cannot end in a fluid but it must extend to the boundaries of the fluid or form a closed path as a ring vortex. This rings transport momentum and the magnitude of this momentum is proportional to the product of its area and the circulation (vortex strength). So the vortex rings carry kinematic energy that is transferred from the swimmer to the water in the form of kinetic energy whenever a vortex is shed. The amount of energy of a vortex lost to the water is proportional to the strength squared divided by the square root of the vortex strength.

Another factor that will affect P_k and thereby e_p is the size of the propelling surface. We can suppose that small propelling surfaces will push off from a small mass of water, while larger hands will push off from larger masses. So for the same propulsive force and with the same technique the swimmer with smaller hands must give a larger velocity (u) to the water. Consequently the loss of kinetic energy to the pushed away water will be larger when pushing off with smaller hands. This suggest that large propelling surfaces (large hand area) give a performance advantage. This can be seen also from a mathematical point of view:

$$e_p = \frac{P_d}{P_d + P_k} = \frac{\bar{D} \bullet \bar{v}}{\bar{D} \bullet \bar{v} + \bar{F}_p \bullet \bar{u}}$$

If we consider only drag forces are generated by the hand, then $\bar{D} = \bar{F}_p$. The previous equation can be developed as:

$$e_p = \frac{1/2\rho v^3 C_{db} A_p}{1/2\rho v^3 C_{db} A_p + 1/2\rho u^3 C_{dh} S} = \frac{1}{1 + \sqrt{\frac{C_{db} A_p}{C_{dh} S}}}$$

with C_{db} coefficient of drag of the body, A_p frontal area of the whole body, C_{dh} coefficient of drag of the hand and S the frontal area of the hand. In this formula we can see that an increase of S leads to an increase of e_p.

From the first law of thermodynamic we know that energy can be neither created nor destroyed. So we suppose that swimmers convert metabolic energy to heat, to energy for internal organs and to mechanical energy necessary to generate the propulsion and overcome the resistive force of the water. Energy conservation implies that a balance must exist among these various forms of energy and also the rate of energy conversion must be in balance. From that we can conclude that also a power balance should exist.

The power balance during steady state can be described as:

$$P_o = e_g \dot{E}$$

e_g is the gross efficiency and reflects that not all metabolic power is converted to mechanical power: in fact a part of it is converted to heat or it is used to support other body functions. Since P_o equals $\frac{P_d}{e_p}$ then:

$$\dot{E} = \frac{P_d}{e_p e_g} = \frac{Kv^3}{e_p e_g}$$

This suggests that the rate of energy expenditure is determined by:

- swimming velocity;
- drag factor K;
- gross and propelling efficiency.

This equation seems to be true as long as the energy spent in accelerating the body is negligible.

We also have to affirm how the majority last in a short period of time ($\pm 2'30''$). So it is obvious that a considerable part of the total power production derives from the immediate (ATP-CP) and the short term (anaerobic glycolysis) rather than the long term (oxydative or aerobic system) power production systems. In figure Figura1.35 is shown the diagram created by Costill [26] in which we can see the relative contribution of the different power systems dependent on the distance swum.

Many models were created to comprehend the mechanisms of aerobic and anaerobic production in swimming but nowadays any of them seems to have a general relevance. It will be necessary to deepen the study on this argument to clarify what are the contributions of the different mechanisms in production of energy from a quantitave point of view.

1.4 Reference Area and General Aims of the Thesis

The present work can be located in the big area of sports devices. In general a sport device is a tool that can help to asses if one or more training session has improved, or not, the physical condition of an athlete. These instruments played an important role in the determination of quantitative indices referring to some features of swimming techniques that also an expert trainer can't see because of the particular environment in which he has to do his evaluations.

Nowadays the spread of these technologies is in a continuous expansion in every industrial field from the healthcare to the automotive. The biggest innovation brought by wearable technologies is their simplicity of utilization and their comfort. In particular, when talking about technologies for sport, it is easy to think how the presence of big sensors or devices on the body surface of the athlete would avoid a physiological movement so that the performance wouldn't be as natural as it has to be. On the contrary if the sensors and their microcontrollers are integrated, as far as it is possible, in the technical clothes, the device let the athletes be free from any impediment.

In this project, with the help of my tutor, we decide to improve a device for the evaluation of swimmers based on a previous device realized by the team of the Sensory Lab and the Design Department of *Politecnico di Milano*. The main aim of my work has been to realize a computer interface for the offline signals processing of the output derived from accelerators located in the electronic positioned on a swimsuit. We propose us to extract some features from the acceleration signals and to show them with a simple and intuitive user interface capable also to furnish a report of training sessions so that the trainer can observe the improvements during all the training period in swimming techniques of swimmers. Furthermore, once we will have complete the algorithm, we will validate the device on different kind of subjects with a specific protocol. This session of testing will be recorded to give evidence of the reliability of the device.

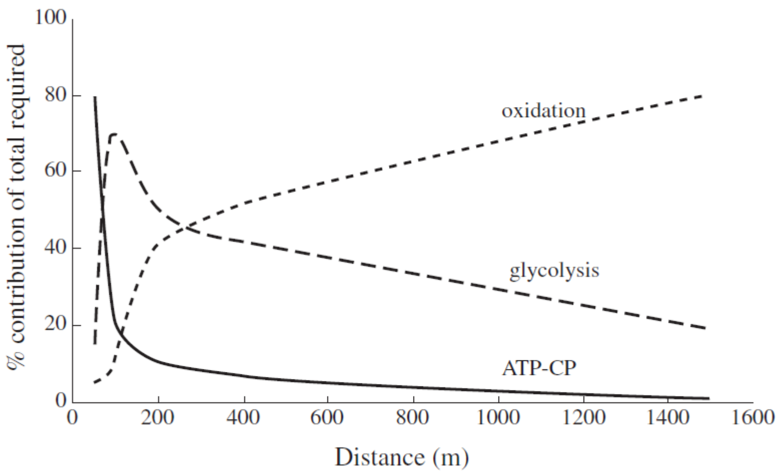

Figura 1.35: Relative contribution of the ATP-CP, glycolytic, and oxidative energy system dependent on race distance

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Capitolo 2

System Development and Design

2.1 Wearable Device: an introduction

The first problem in detecting the quality of the technique of an athlete is that is very difficult to reproduce the movement in a movement analysis laboratory. It is for that reason that, in the past, the evaluation of sportive gesture were made thanks to video recording and photo shooting.

Many attempts were made in order to bring technologies in sportive place as indoor gym or outdoor. It's easy to think how difficult was to organize trials and how many time and money were spent in order to evaluate athletes' performances.

With the invention of MEMS technologies and the creation of miniaturized sensors now it is possible to create portable and non intrusive device able to comprehend and analyze different kind of movement.

Nowadays the spread of wearable technologies are a huge phenomenon due to a greater interest in monitoring different activities and health.

At the beginning the interest in wearable device was mainly oriented to medical applications. We can affirm how the impulse in this field of research was given by the attempt to involved the user and their families in prevention, diagnosis and treatment of various kind of pathologies [30].

Furthermore, in the last few years, shorter hospitalizations and better home care are the new tendency in every national health service organization. From this point of view we can understand the great importance of wearable technology because it can support the patient anywhere. This conditions let the rise of Wearable Biomedical Systems (WBS).

WBS are generally composed by four elements [18]:

1. Human Machine Interface layer: it is constituted by a transducer able to perceive bio-electrical/chemical/physical properties or signals of the

human body, or otherwise to deliver to the body itself electrical or chemical drugs or other substances, or physical signals/actions. For these purposes different solutions as textile electrodes and micro actuators for mechanical actions were created;

2. Connection solution: this is the input way to the case where electronics is inserted;

3. Case: it is directly related both to the electronics and to the body location;

4. Electronics: it has to be divided in two parts respectively the analogue front end for signal sensing and the pre-processing (conditioning circuits), and the digital part for the control of and the data processing.

An important role in WBS is covered by the communication. We can divided two kind of communication:

1. Communication between the device and the user: buttons, displays, LEDs that constituted the interaction elements between user and device;

2. Communication between the device and a remote point: this problem is solved by the use of different technologies like mobile GSM UMTS device, commercial Bluetooth/WiFi embedded or Wireless USB options.

The example given by this kind of device in the health-care field makes the market think a possible application in sport and movement analysis area where often it is difficult to have quantitative data with portable and low cost technology.

The creation of wearable devices for sports evaluation brings many advantages:

- They help trainers in the quantitative evaluation of technical movement they can prepare the athletes with training sessions supported by a solid numerical evidence. This also let the athletic trainer to assess improvements and quality of technical gesture execution;

- These device make people to be more active and to do exercises with a electronic supervisor: people can do their exercises in safety and keeping trace of their health status. This has also a positive impact on the general healthiness of the population.

- Wearable devices let the movement be more ecological: there aren't cables or other impediments for the athletes movement.

Considering swim, we can affirm how it requires complex movements supported by a really complex biomechanics. Furthermore we have to consider also the particular environment in which swimmers has to train which prevents the use of optoelectronic instrumentation. All these considerations bring us thinking how wearable technologies have, in this field, a great potential because they can overcome all the described problems.

If we see wearable device market for swim detection and analysis we can immediately saw that are full of devices but no one of them is, from a technological point of view, ready to totally support the user requests.

2.2 Market Research

2.2.1 Xmetrics

Xmetrics [15] is a wearable device (Figura 2.1) that can be positioned on the back of the head with a clip situated on the goggles.

Figura 2.1: Xmetrics fit

.

It can record different biomechanical parameters and also gives a real time audio feedback via earplug. In this way a swimmer can receive an audio feedback about laps count and timing, number of stroke and so on and later, after the training session, he can observe his improvements and his performances.

They propose two version called *Xmetrics Fit* and *Xmetrics Pro*: the first one is a device that is thought for every person who wants to enjoy swimming from non professional to occasional swimmers. On the contrary the second one, as suggests its name, is the specific version for professional swimmers.

Both give, as feedback, the lap and timing count, swimming efficiency and can detect the specific style. In the plus version a swimmer can customize the real time audio feedback, receive a flip turn analysis, program his training sessions. It is also possible to share data with coach (only in the Pro version) and social media. Tabella 2.1 shows pros and cons of the devices and their market prices.

Pros	**Cons**
Real-time customizable audio-feedback Designed for Pro Swimmers Flip and turn analysis It can be adopted by pro swimmers	Positioned far from the trunk and leg No heart rate feedback No information about body orientation
Price: € 299, 99	

Tabella 2.1: Xmetrics: Pros and Cons

Note thate this price is related to the Pro version. The fit version has a price of € 199, 99.

2.2.2 Moov

Moov [7] is a sports monitoring device for able to evaluate and give feedback on performances of different athletic disciplines.

It consists of small electronic integrated sensors enclosed in a round waterproof case (Figura 2.2). In particular it has a 9-axis motion sensing system that recreates and analyzes the 3D motion of bodies. Its hardware is composed of magnet, angular rate and gravity sensors and the software reconstructs the 3D motion. It can be located in different positions on the basis of which sport movement the athlete wants to evaluate. For the evaluation of swimming performances, Moov is situated, as a bracelet, on the wrist of the athlete. The software *Moov Swim* makes an offline evaluation of the signals taken by the electronic system. It measures lap time, flip turn time, resting time, pace, the mileage covered by each stroke and the average stroke rate. Through the app, it is possible to compare data of different sessions and find out the improvements. Tabella 2.2 reports pros and cons of the previous described activity tracker.

Figura 2.2: Moov

.

Pros	Cons
Software for $3D$ motion reconstruction	No body orientation analysis
Different kind of performance indicies	No heart rate feedback
	No real time feedback
	No suitable for professional swimmers
Price: € $104,54$	

Tabella 2.2: Moov: Pros and Cons

2.2.3 Misfit Shine

Shine [11] is an activity tracker made of anodized aluminum with an electronics encapsulated in a round case (Figura 2.3).

Its dimensions are $27.5x3.3x27.5mm$ with a weight of 9.4 grams: these features let the device be more comfortable. It is possible to wear it in different ways giving the device the opportunity to be positioned in different place, with its magnet, on the basis of which sport or movement the athlete has to do. In particular it can be positioned on:

- Chest;

Figura 2.3: Misfit Shine

.

- Wrist: it is worn as a watch (suggested for sleep monitoring and swimming);
- Waist;
- Ankle (suggested for cycling);

It has a LED screen and it is equipped with a button cell (watch battery) with a maximum duration of six months. Its waterproofness arrives to an underwater depth 50 meters. It has only a three axis accelerators and

Bluetooth technology (Bluetooth 4.0) for the synchronization. With Shine it is possible to measure paces, calories, quality and duration of sleep.

In particular for swimmers, it gives to the athletes a poor feedback. It considers swim an activity (with respect to timing and burned calories) but doesn't record distance, SWOLF or other data. In Tabella 2.3 the principal pros and cons of Shine and its market price are summed .

Pros	**Cons**
It can be worn in different position	Swim is considered only as an activity No heart rate feedback No professional device No real time feedback
Price: € 87, 84	

Tabella 2.3: Misfit Shine: Pros and Cons

2.2.4 Polar V800 and Swimming Metrics

For the evaluation of sports techniques and performances, Polar, a famous brand in sports market branch, proposes for the athletes a watch able to measure and quantify some characteristics with the help of a specific software.

Polar V800 [8] registers every training session and the daily activities. It shows the work made and the necessary time of recovering. With its integrated GPS, it can show also speed, distances and the trackway made by the athlete. Furthermore it gives the opportunity to create customizable sports profiles and it offers also a specific profile for multisports activities with recognition of transition times. With Polar Flow mobile app data are synchronized, using Bluetooth technology, with athletes' smartphone and it's possible to visualize the heart rate, also when it is submerged in aquatic environment on the watch. Its impermeability reaches 30 meters underwater.

Considering swim, this watch is able to monitor swimming performances through the automatic acquisition of style, distance, speed, number of strokes and recovery time. With Swimming metrics, a specific swimming software, it is possible to analyze each swimming session and to follow the performances and progress in the long run. In addition to the features we've described before, it gives the possibility to calculate the SWOLF score, an important elements to keep track of improvements in swimming efficiency. It's important to observe how, in swimming profile, GPS is not available and distance and pace measurements are based on the insert by user pool length. It is optimized only for freestyle technique. Swimming drills are not supported.

Figura 2.4: Polar V800

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In particular V800 records:

- Pace and Distance: this measurements are based on pool lenght that is set by user. It also recognizes turn and uses this information to calculate pace and distance;
- Strokes: Polar V800 shows stroke rate and how many strokes you take per pool length;
- Swimming styles: this watch recognizes swimming styles and calculates styles specific metrics and totals for the overall session. The styles recognized by Polar V800 are: freestyle, backstroke, breaststroke and butterfly. In its online site the company specify that style recognition works best with freestyle and that external factors can affect swimming style identification.
- SWOLF: it is an indirect measure of efficiency. It is calculated by adding time and the number of strokes taken in a pool length. Generally the lower your SWOLF is for a certain distance and style, the more efficient you are;
- Calories burned: there are two ways used by this watch to calculate energy consumption. The first one is the more accurate and it is given by the acquisition of the heart rate through a specific hear rate sensor. However, if the swimmer doesn't wear the sensor, it gives a summary index based on the wrist movements using the accelerometers.

An overview of pros and cons of Polar $V800$ is presented in Tabella2.4.

Pros	Cons
Automatic style detection	Optimized only for crawl style
Good analysis of swim	It is needed the chest belt for the heart rate measure
Heart rate detection	It has to be improve so that it can be adopted by pro swimmers
Price: € 449, 90[1]	

Tabella 2.4: Polar V800: Pros and Cons

2.2.5 Instabeat

This kind of device [6] is mounted on the straps of any type of swimming goggles (Figura2.5). With this dispositive one should be able to visualize the heart rate zone in real-time on the lens during training. In particular the device can distinguish three different zones and gives to the athlete a feedback based on a colour code. If on the goggles the swimmer sees a blue light he is in the fat burning zone, if he sees a green light he is in the fitness zone and, at last if he sees a red light he is in the maximum performance.The heart rate is measured from the temporal artery. To collect the data it is

Figura 2.5: Instabeat

necessary to connect Instabeat to the USB port on computer. In addition Instabeat measures the principal training parameters as calories, number of laps, number of flip turns and the breathing pattern. Then there is the possibility to create a customized profile and determine the heart rate zones. Instabeat has four sensors:

1. Three axis gyro;
2. Accelerometer;
3. Magnetometer;
4. HR light sensor.

Its water resistance is limited at 30 meters. It is equipped with a 9 color LEDs display (three for each colours) and has a Lithium Polymer battery with a capacity of 8 hours. A detailed description of pros and cons of Instabeat can be seen in Tabella2.5.

Pros	**Cons**
Heart rate feedback in real time on goggles lens Breathing Pattern Good analysis of swim Useful for pro swimmers	Far from trunk and legs
Price: € 149	

Tabella 2.5: Instabeat: Pros and Cons

2.2.6 Swimsense Performance Monitor Finis

The Swimsense [13]is a training tool able to capture performance data. The monitor can be positioned on the wrist like a watch.

It uses accelerometers and proprietary algorithms to analyze the performance of the athletes. It is equipped with a rechargeable lithium-ion battery with a capacity of 12+ hours of swimming use.

With regards to swim, it measures:

- pace time;
- distance in meters, yard and laps;
- stroke count;
- stroke rate;
- distance per stroke;

- calories burned;
- SWOLF efficiency score;

These features of swimmer's technique are analyzed for every kind of style. These data can be upload for an additional offline analysis and an historical review (up to 14 past workouts on the monitor and many other can be save and register on computer).

The user has to set:

- Pool sizes;
- Meters;
- Gender;
- Weight.

It is also possible to create workout plans and compare against your actual workouts. To rightly configure the device, the user has to add also the information about the position of the watch (left or right wrist).

An interesting feature of this monitoring electronic instrument is what the company calls iiM (Interval Inference Mode). This option let the athlete to have an idea about intervals and rest time so that he has not to press any button on the watch while swimming. Otherwise this feature seems to work only under restrict conditions as:

Figura 2.6: Finis Swimsense Performance Monitor

.

- Push off strong: the swimmer has, on each wall, to push off and streamline for at least two seconds;
- Finish Strong: the finish has not to be short because, in that case, it cannot measure accurately the time of intervals;
- Be still between intervals: the athlete has to be still as long as possible because every motion can be recorded as a start of the activity;
- Have at least 3-5 seconds rest between intervals: the watch needs this time to know that swimmer has stopped swimming. Otherwise it should think the athlete is doing a very slow turn.

In the Table below (Tabella 2.6) are shown pros and cons of Finis Swimsense.

Pros	**Cons**
Designed for Swim Automatic detection of stop and rest (IiM) Useful for pro swimmer	No real time monitoring IiM requires specific and severe conditions
Price: € 149, 34	

Tabella 2.6: Swimsense performance monitor Finis: Pros and Cons

2.2.7 AquaPulse Finis

This device [2], shown in figure Figura2.7 has the purpose to give the customer information about heart rate.

In particular the heart rate is announced during the training directly to the swimmer. It can be located on the goggle strap and by attaching the clip to the earlobe. The heart rate is kept trough an infrared sensor that monitor the capillary blood flow. Then it is communicated in real time using the inner ear via Bone Conduction Technology.

It has a lithium ion rechargeable battery that guarantees an autonomy up to eight hours. To recharge the battery, the device has to be connected with an USB port of a PC. All the pros and cons of the device are described in Tabella 2.7.

2.2.8 TomTom Multi-Sport GPS Watch

TomTom Multi-Sport GPS Watch [14] is a device to get many information about a several kind of sport as indoor running, outdoor running, cycling, dedicated bike mount and swimming (Figura 2.8).

The display size is about $22x25cm$ and it can work till a depth of fifty meters. The battery lifetime let the device work till eight/ten hours.

Pros	**Cons**
Real time heart rate monitoring Useful for pro swimmer	No other feedback on swim technique
Price: € 114, 20	

Tabella 2.7: Aquapulse Finis: Pros and Cons

It uses GPS and GLONASS technologies[2] to obtain information about the location of the athlete that, with a non real time signla processing, let the proprietary algorithms to extrapolate different swim features. It is equipped also with a magnetic and an indoor tracker sensors. It communicates with Bluetooth Smart technology.

When it is set on swimming mode, it can be able to capture swim metrics in pool. In particular it registers:

- Distance;

[2]GLObal NAvigation Satellite System: it's the counterpart of the Global Positioning System and it is managed by the Russian space force. Usually, to obtain more accurate information, the two technologies, GPS and GLONASS are used together.

Figura 2.7: Finis Aquapulse

.

- Strokes;
- Time;
- Swolf.

Once the user has selected the activity, he can also set he pool size. With this watch, the user can choose between different modes:

- Goals mode: The user can be able to specify a total distance, time or calories target. It is possible to see the progress updates towards the goal;
- Interval mode: The user set the distances, the work period, the rest period and the cool down period;
- Lap mode: this allows to automatically create laps after a specified time or distance.

In Tabella 2.8 pros and cons of Tom Tom Multi Sport GPS watch are shown.

2.2.9 Speedo Aquacoach

Speedo Aquacoach [12] is a watch designed only for swimmers (Figura 2.9). It uses the technology licensed by Swimovate which algorithms calculate the major and important features in swim training. In particular it detects:

- Strokes;

Figura 2.8: Tom Tom Multi-Sport GPS Watch

.

Pros	**Cons**
Three different modalities	Few technique indexes No information about velocity Not suitable for pro swimmers
Price: € 149, 00	

Tabella 2.8: Tom Tom Multi-Sport GPS watch: Pros and Cons

- Number of Laps;
- Times of Laps;
- Average Strokes;
- Distance;
- Calories Burned.

It hasn't got an integrated GPS because it was created only for an indoor training.

It works with every swimming style and recognizes turns. It works until a depth of 100 meters is reached and only in pool over 15 meters length. Before swimming it is necessary to insert the pool length.

Regarding memory, this watch is able to keep in mind 50 workout.

In Tabella 2.9 pros and cons has been figure out.

Figura 2.9: Speedo Aquacoach

.

Pros	**Cons**
Designed only for swimmer	Few technique indexes
A great number of information	No information about velocity
Recognizes turns	Not suitable for pro swimmers
Price: € 90, 00	

Tabella 2.9: Speedo Aquacoach: Pros and Cons

2.2.10 Garmin Swim

The Garmin Swim [5] belongs to the category of wrist watches (Figura 2.10). It is not equipped with GPS, so it is not indicated for those who swim in open water and it doesn't give information about athletes location. As a consequence of that the swimmer has to insert the pool length. It has accelerometers and gyros that, with appropriate algorithms, can tell you some information about your swimming technique and its effectiveness. Its physical dimensions are $4.8x1.3x4.4cm$ and the battery is a $CR2032$ with a lifetime of about 1 year. It recordes:

- Strokes Number;
- Lengths;
- Times: it shows time of laps and also total time of the training session;
- SWOLF.

The swimmer can also tell to watch if he is in a rest phase by pressing a push button. In this way it comprehends that this time will not affect the calculated performance indicies. Positive and negative features of Garmin Swim are repoted down below (Tabella 2.10).

Pros	**Cons**
Recognition of rest phase (not automatic)	Few and very general indexes
Stroke type identification	No information about velocity
	No info about heart rate
	No info about body orientation
Price: € 133, 98	

Tabella 2.10: Garmin Swim: Pros and Cons

2.2.11 Swimovate PoolMate

Swimovate PoolMate[9] is a watch that automatically identifies lap and stroke in every style. Swimovate (Figura 2.11) let the swimmer choose between different kind of watch:

- PoolMate: it is the “zero” version of the watch;
- PoolMatePro: this version let you download data on you computer;
- PoolMateLive: this particular watch gives the swimmer a real time vibrational feedback during swimming;
- PoolMateHR: this device it’s the only one of all serie to give the athlete information about the heart rate.

Because the last one is the most interesting and complete version, we go deeper in describing it.

The watch has a weight of $67g$ and the diameter of face is about $48mm$. It has a battery life around 30 days. It uses inertial sensors as a IMU[3] to receive data. Then, this data, are elaborated with a specific algorithm to give to the athlete information about the most interesting features of swim technique. In particular the user can visualize:

[3] It is not specified what kind of sensors they use. They only refers to “motion sensors able to detect the motion of the arm. So, the use of an IMU is only an assumption based on a review of the state of art about this kind of device

Figura 2.10: Garmin Swim

.

- Laps;
- Strokes;
- Mean Speed;
- Distance;
- Calories;
- Stroke Length;
- Stroke per Minute;
- Efficiency.

Furthermore it furnishes a vibrating alerts when the swimmer swims at a certain number of laps, distance or time interval. It can be use in different ways:

Figura 2.11: Swimovate PoolMateHR

.

- if the swimmer makes the watch vibrating every n number of laps he can immediately understand how many laps he has done;
- The swimmer can also set the vibration start every M meters. So when the watch begins to vibrate, it tells the athlete he has done the relative distance;
- The user can set the vibration to go off after any long time period. In this way he can knows if he has swum for his allotted time;
- The swimmer can set the vibrate alarm to start after a determinate slot of time. He can also set the buzz ringing after a determined distance. In this way the athlete can understand if he is swimming at a correct pace or not.

The heart rate is obtained through the use of a chest belt. The surprising element is not the belt itself but how can it works underwater. They tell us their sensors use a lower frequency in respect to that use in other watches (that has a typical value of 2.4 GHz). Nevertheless the specifications about this choice are not reported. The main characteristics, pros and cons of this device are reported in Tabella 2.11

Pros	**Cons**
Designed only for swim Info about heart rate (using chest belt) Real time feedback (vibrating alerts)	No info about body orientation Heart rate sensor not integrated in the device
Price: € 220, 69	

Tabella 2.11: Swimovate Poolmate HR: Pros and Cons

2.2.12 Amiigo

Amiigo [1] is a wristband (Figura 2.12)or bracelet that is able to detect, through the use of motion sensors, the upper body activity.

It is thought not only to help athletes to keep trace of training sessions, but also to give a feedback about the health conditions.

It is equipped with a three axis accelerometer, a temperature sensor and a pulse oximeter. It is made of PC and ABS plastic and it has got a lithium polymer battery with a capacity of 2 days.

It measures:

- Heart rate;
- Blood oxygen saturation;
- Heart rate variability;

Figura 2.12: Amiigo wristband

.

- Blood pressure variations;
- Skin temperature range;
- Pulse volume variation;
- Calorie burn rate;
- Respiration rate.

In swimming Amiigo track laps, strokes and time. It also recognize the 4 main styles: breaststroke, backstroke, freestyle and butterfly. The main pros and cons of Amiigo are shown in Tabella 2.12.

Pros	**Cons**
Detection of four styles Good for the monitoring of health condition	No info about body orientation no info about heart rate Not recommended for pro swimmers
Price: € 159, 73	

Tabella 2.12: Amiigo: Pros and Cons

2.2.13 Jaybird Reign

The Jaybird Reign [10] is an activity tracker bracelet(Figura 2.13): it recognizes sports, monitors your sleep and its quality and tells you your ideal daily activity temporal target.

Figura 2.13: Jaybird Reign Bracelet
.

Reign automatically recognizes which activity the athletes have done and show them how long they have been active.

It is equipped by motion sensors, as a three axial accelerometer[4], and, with an accurate signal processing, it discriminates which activity has been done.

It is equipped by an heart rate sensor located in the internal part: it is thought to be in contact with the skins. We can suppose it is simply realized with a coupling of light emitting diode and a photodiode. It is used mainly to understand how the athlete is prepared to support the daily activity, considering the heart rate variability, and to suggest him how many time he has to spend in an active condition[5].

For what concerns swim, it is only recognized as an activity but it doesn't tell you specific information about your technique or performance. Indeed its target isn't to coach and let the swimmer be aware of his preparation but only to give a feedback on how many time he spends in an active status. In Tabella 2.13 are reported the main pros and cons of the previous described device.

[4]The information about the hardware are hidden by the inventors so it's only an assumption made on the basis of what it can do.

[5]They calls this function "Go Zone"

Pros	**Cons**
It gives a visual feedback (training time)	No technical information Feedback only on time and calories burned Not for pro swimmers
Price: € 175, 66	

Tabella 2.13: Jaybird Reign: Pros and Cons

2.2.14 Flyfit

Flyfit [4] is a device that is worn around the ankle. It captures leg movement and tracks different activities. It is useful also to analyze your sleeping time and the quality of sleep. Flyfit (Figura 2.14) provides wireless synching with Bluetooth 4.0 technology.

The modules dimensions are $33x20x15mm$ and its weight is under 12 g. It has a rechargeable Li-ion polymer battery with a life of up to 5-7 days (with off sync mode) or 8 hours (with a real-time sync mode).

Figura 2.14: Flyfit Smart Ankle Tracker

.

It has different lights: three of them indicate in which modality the user are and the last one indicate the level of the battery. There are three mainly modes in which the device operates:

1. Sun-Day Mode: in this mode Flyfit tracks steps, running and cycling;
2. Moon-Night Mode: the device in this status tracks sleeping quality;
3. Drip-Swimming Mode: this specific mode is useful when swimming.

Specifically for swimming, the last mode can track swimming style and kicks. These are the only two information the swimmer can obtain from FlyFit ankle tracker. Given its poorly feedback, we can suppose that, inside the hardware, there is only a three axial accelerometer and a GPS that, as we know, can't work inside the pool. Later signals are processed and the features of the specific activity are detected.

Pros	**Cons**
Specific swimming mode Keeps trace of lower limbs movement Track swimming style	Only few indexes Not for professional swimmers
Price: € *N.A.*	

Tabella 2.14: Flyfit: Pros and Cons

2.2.15 Atlas Wristband

Atlas Wristband[3], as suggests its name, it's a wearable device that can be worn as a bracelet (Figura 2.15). It identifies exercises, let you know how many calories you have burned and gives you a qualitative opinion about your physical form.

It has two $32bit$ ARM $M4$ Processors and a $128-by-64$ pixel resolution white PM OLED touch screen input. The battery is a 120 mAh battery Lithium Polymer and it uses the Bluetooth Smart technology to communicate (Bluetooth LE). Three kind of sensors are integrated in the hardware:

- 3 axis accelerometer;
- 3 axis gyroscope;
- Optical heart rate sensor.

It is water resistant up to 50 meters of depth.

It uses a machine learning algorithms to track the $3D$motion of the user so that the more he trains the better it recognizes different kind of activities or exercises. An interesting feature of this device is that tells which muscles the athlete has strengthened.

It can work in three different modes:

Figura 2.15: Atlas Wristband

.

1. Freestyle mode: the user can work doing what he wants. The device registers the exercises, heart rate, forms and everything he wants;

2. Coach mode: in this mode the user can create and find workout routines, a vibration alarm, and a smart timer mark the beginning and end of sets while tracking reps, rest and active time as measures of endurance;

3. Watch mode: this mode can be turn on while the user is not working. The pedometer continues to calculate the pace so that let the user know his overall health and lifestyle.

The heart rate sensor allows to monitor the heart rate in real time. The information given by this sensor, combined with specific biometrics laws, permits to have an idea of the burned calories during the workout.

For what concerns swimming, it has not been released yet the ultimate firmware, but they let us know from their websites that they are going to give to swimmers the possibility to know the number and type of strokes, calories burned, muscles groups worked and heart rate. The algorithm will learn the motion pattern so that he can accurately detect the style and it will improve the detection with its usage. Pros and cons of the described device are shown in Tabella 2.15.

2.2.16 Overview: Comments and Comparisons

We substantially can divided the analyzed swimming monitoring device in three different categories:

Pros	**Cons**
Use of learning machine	Positioned on wrist
Gives a feedback on muscles involved	No info about velocity
Info about heart rate	No info about body orientation and asymmetry
	No realtime feedback
Price: € 222,00	

Tabella 2.15: Atlas wristband: Pros and Cons

1. Wrist watches;

2. Bracelets or anklet;

3. Devices positioned on goggles.

The first classes presents always, except for a few models, an high complex electronic system. The problem is that this represents an advantage for sports that doesn't involved water. Indeed, if we think for example to GPS, it doesn't work underwater so that the location of the swimmer becomes unknown and this function becomes futile. Talking about swim, watches are not able to keep trace of body orientation. This doesn't let the trainer, manly at a proficiency level, to go wider and to improve the training plain. For what concerns heart rate, we have seen from the previous market research, that the market prefers heart rate sensors based on optical technologies (LED- photodiode coupling). This can be useful for that activities that doesn't require the immersion in aquatic environments. The other choice made by some companies is to improve chest belt technology and track the heart rate also when the body is submerged. This is a good idea from a technological point of view but, if we think to the comfort of the athlete, he has the chest constraint so that the movement becomes less natural as it would be and, furthermore, the swimmer has to remind himself to wear two devices instead of one (excluding the higher cost of versions that provides also the belt).

Adverting the second class, we can assert how that devices are frequently designed to be only "activity supervisor"and not activity tracker. In fact they only recognize time spent in sport and estimate calories burned: nothing more. This is due on one hand to their simple electronic and, on the other hand, to their location that doesn't let to go deeper in the biomechanical analysis. We can also affirms how the designers have given more importance to the shape and style contrariwise the performance. In general they are not indicated for training of professional athletes but they can be used by people to obtain and regulate their active time to gain an healthier lifestyle.

Passing to the last class, we can conclude how it represents an intermediate choice between the two previous one. The main problem verified studying this kind of devices is their position: they are positioned on goggles and we have to consider that the head in hinged with the trunk so that the two movement are often not the same. This creates errors in biomechanics patterns recognition mainly considering strokes. On the other hand this position let the device track the breathing pattern so it can conclude something more on the efficiency and management of swim motion. Furthermore it is more interesting comprehend how engineers have solved the problem of the heart rate detection. They searched a non invasive method to get information about the heart functioning: in particular Finis Aquapulse has positioned one clip on the earlobe and Instabeat keeps the heart rate from the temporal artery. Surely, in a first approximation, we can affirm how this signal is far from the electrocadiografic one but it is useful for the purpose they've invented it.

When evaluating the performance of a swimmer, one of the most important information related to the energy consumption and the efficiency is the heart rate. From the market research it has been observed how most of them can't keep trace of the heart functionality. This is due to the complexity in the design of a relevation system that can overran the problems given by the hostile environment. In relation to Figura 2.16 that only the 26% of devices analyzed can keep trace of heart rate and, between them only the 13% doesn't need two different devices to let the swimmer know his heart condition. This point out a big problem to solve in the product realization phase and engineering of this swimming tracker.

From a subjective point of view supported by the market research, I've tried to classify, on the basis of the feedback given by the particular device, each activity tracker in "Activity tracker for pro swimmersand "Activity tracker for non pro swimmers. For what concern this research, we can see in Figura 2.17 the division between the two kind of devices. We can observe a small difference between the two categories. Nevertheless, it has to be reminded that this is only a restricted research. As a matter of fact we have on market lots of devices that pretends to analyze sport mechanics but are only basic activity tracker. We can conclude that, on market, there are few devices able to really help a pro swimmer and his trainer to evaluate performances. So there is already a big opportunity in developing device able to go further and improve the state of technologies with the aim of giving an objective and important feedback to trainers and swimmers themselves.

In Figura 2.18 are shown devices' prices. It is possible to note how they all, except for Polar V800, Shine and Aquacoach, are similar. From a general point of view, an higher cost is associated with a more complex technology. If we look the picture, we notice how Xmetric has a price that is out of the bond delimited by the devices of its class and, in a first approximation,

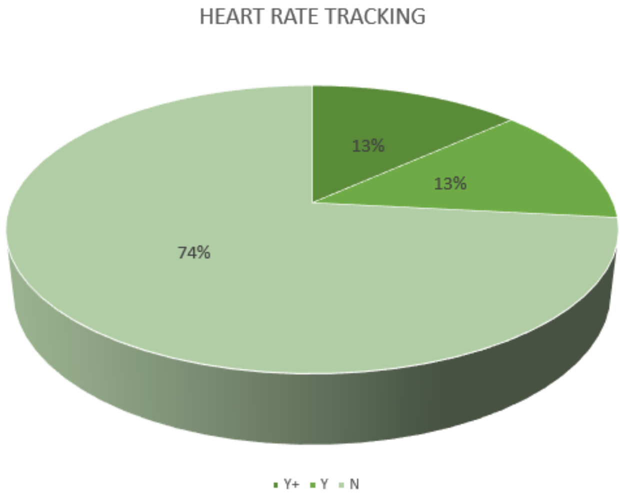

Figura 2.16: Heart rate: this picture shows the results of the market research and compares devices on the basis of which gives heart rate feedback during swim and the other that doesn't give it.In reference to the graph N devices doesn't sense heart rate, $Y+$ devices take trace of heart rate with the coupling of two different devices and Y devices can sense and monitor by themselves the heart rate

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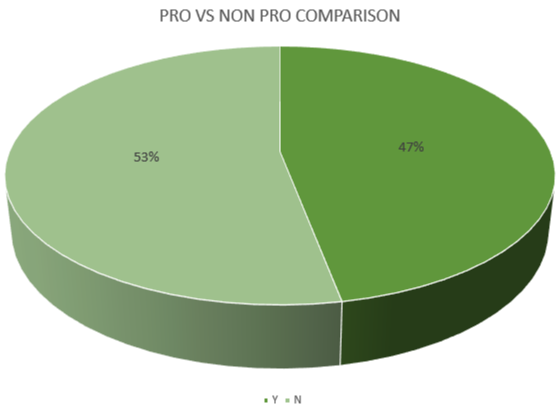

Figura 2.17: Pro and non pro devices: in this graph it has been shown the division between devices for pro swimmer (Y) and that not useful for pro swimmer (N) technique evaluation.

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this position is not justified by its technology because other device, as the TomTom Multi-Sport GPS, have lots of function and a less price. Also Polar V800 is an outlier but, in this case, we think it has to be imputed to a more sophisticated electronic structure and software implementation.

Figura 2.18: Prices comparison

2.3 Hardware and MEMS technology

2.3.1 MEMS technologies and sensors for movement detection

Today the development of nano-technologies has pervaded every technological fields. It refers to dimensions of a device comparable with a nanometer scale (10^{-9}m) nevertheless we usually have device of about 1000 times larger dimensions. However the trend is toward the smallest dimensions as far as the technology allows.

Nowadays the interested in micro miniaturization becomes larger day by day and the microsystem technologies (MST) is undoubtedly the way on which the research has to orientent itself.

A subset of these is the micro-electromechanical system or *MEMS*: a MEMS is a device having electrical and mechanical components, which means there must be at least one moving or deformable part and that electricity must be part of its operations. Most of the sensors that are fabricated with MEMS technology are three dimensional devices with dimensions on the order of micrometers.

With michromachining we refers to techniques used to produce the structures and moving parts of microengineered devices. One of the goals of microengineering is to be able to integrate microelectronic circuitry into micromachined structures, to produce completely integrated systems called microsystems [28].

These technologies has also been applied in movement analysis. In particular one of the crucial sensor in movement detection is the accelerometer.

Generally an accelerometer sensor is formed by an element (inertial mass or sismic element) that, if it undergoes to a certain acceleration, moves with a delay in respect to the housing. There are many different kind of accelerometers on the basis of the type of transduction they apply and to the number of axes they response to. With respect to the first classification we can discriminate between:

- Piezoresistive accelerometer: they have various form of realization and they expoits their function with the use of a elements that changes their resistance in relation to the change of their geometric characteristics (Figura2.19);

- Capacitive accelerometer: in this kind of sensors, electrode are positioned on the sismic mass (movable electrodes) and on the inner part of the houses. When the sismic mass undergoes to an acceleration, the capacitance between movable electrodes and the fixed one changes in relation to the acceleration (Figura 2.20).

The accelerometers can also sense different numbers of axes depending on their fabrication technology. The most useful accelerometer when talking

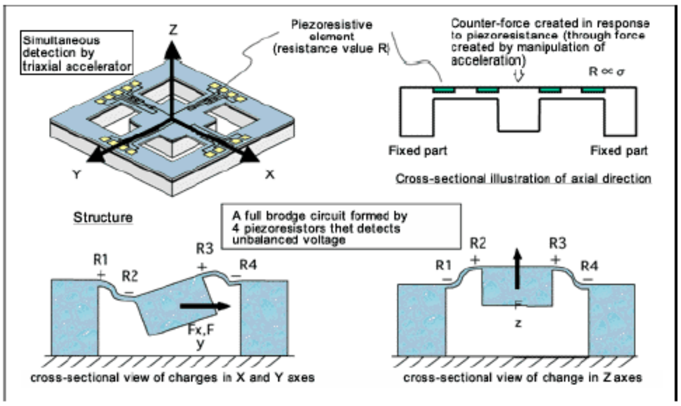

Figura 2.19: A piezoresistive 3-axial accelerometer

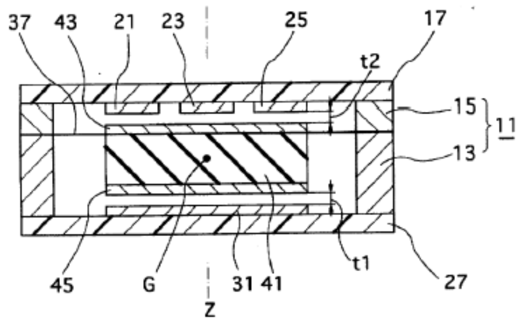

Figura 2.20: A scheme of a capacitative acceleration sensor.

about movement analysis are the so called 3 axial accelerometer. As the name suggests, these accelerometers are sensitive to each of the three axes. They can be realized by adding three different mono-axial accelerometer in the way that each one senses one of the acceleration components.

With the MEMS technology (Figura 2.21), they can be realized in miniaturized chip that can be placed in many kind of devices requiring a very small space. This can help engineers to develop wearable devices that not interfere with movement and gesture.

A more complex and useful electronic device is the so called *IMU* (Inertial Measurement Unit). It measures speed, orientation and gravitational forces using a combination of data given by accelerometers, gyroscopes and magnetometers (Figura 2.22). A mechanical gyroscope (Figura 2.23) is a physical rotating device that, for the angular moment conservation law, tends to maintain its rotational axes oriented in a single direction. When the wheel (rotor) freely rotates, it tends to preserve its axial position. If

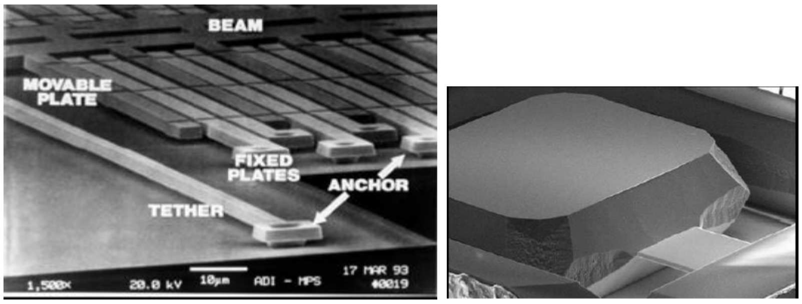

Figura 2.21: Spring, proof mass and capacitor of a bulk MEMS accelerometer (VTI) and the same parts of a surface MEMS accelerometer (Analog Device) at 10× magnification.

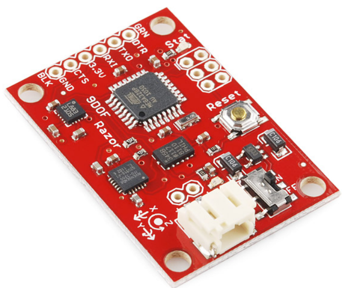

Figura 2.22: Example of a IMU (9 DoF Razor Sparkfun).

the gyro platform rotates around the input axis, the gyro will develop a torque around a perpendicular axis thus turning its spin axis around the output axis. This phenomenon is called *precession* and can be explained by Newton's law:

> The time rate of change of angular momentum about any given axis is equal to the torque applied about the given axes

To determine the direction of precession it necessary to understand that the precession is always in such a direction as to align the direction of rotation of the wheel with the direction of rotation of the applied torque.

The MEMS technology have let the development of miniaturized gyroscopes where the rotating disc has been replaced by a vibrating element. They based their functioning on the Coriolis force. Indeed Coriolis stated that, if Newton laws are applied in a rotating reference system, there will be an acceleration acting right in respect to the movement direction for an anticlockwise rotation and left for a clockwise rotation that has to be included in the motion equations. The Coriolis acceleration acts everytime a body moves linearly in a reference system rotating around a perpendicular axes to the movement direction. In a MEMS gyroscope the rotation has been replaced by the vibration. Instead of a mass following a circular trajectory, the mass can be suspended and made to move linearly and vibrate. So the relative acceleration can be revealed and it depends on the sensor motion. Figura2.22).

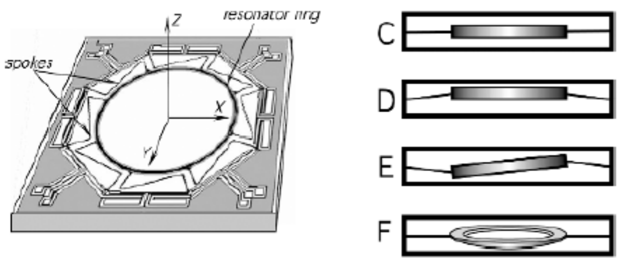

Figura 2.23: Example of a structure of a MEMS gyroscope.

Magnetoresistors are useful in the measurement of linear and angular displacements, rotation, position and angle. As we know, a magnetic field applied to a current carrying conductor exerts a Lorenz force on electrons (that is always perpendicular to the direction of charge carriers) that deviates some electrons from their path having an effect on their trajectory. If the relaxation time due to lattice collisions is relatively short, electron drift to one side of the conductor yields a transverse electric field that opposes further electron drift. However if that relaxation time is relatively large, there is a noticeable increase in electric resistance: this determines the magnetoresistive effects. In particular, considering magnetoresistors contained in a IMU, their functioning is based on the concept that a moving object must modify a magnetic field. To accomplish this there could be a metallic object placed in a constant magnetic field or the moving element to be detected must incorporate a permanent magnet because whenever the magnetoresistive sensor is used as a proximity, position or rotation detector, it must be combined with a source of magnetic field. With this sensors can be detected also the angle formed by the object with a reference line: in this case magnetoresistors are called tilt sensors.

2.3.2 Hardware

The hardware of the device is shown in Figura 2.24 and in Figura 2.25.
It can be divided in five main blocks:

1. Micro-controller;

2. Inertial Measurement block;

3. ECG block;

4. Memory block;

5. Energy supply block.

They will be analyzed, one by one, showing each components and their main features.

Micro-controller Considering the micro-controller, it has been used an Arduino Micro Figura 2.26.

It has 20 digital input/output pins (of which 7 can be used as PWM and 12 as analog inputs), a 16 MHz crystal oscillator, a micro USB connection, an ICSP header and a reset button. The main features of the chosen board are shown in Tabella 2.16.

Operating Voltage	$5V$
Input Voltage	$7-12V$
Digital I/O Pins	20
PWM Channels	7
Analog Input Channels	12
DC Current per I/O Pin	40 mA
DC Current for $3.3V$ Pin	50 mA
Flash Memory	32 KB
SRAM	2.5 KB
EEPROM	1 KB
Clock Speed	16 MHz
Length	48 mm
Width	18 mm
Weight	13 g

Tabella 2.16: Arduino Micro: Main Features.

This choice has been made mainly to overcome the problem of its encumbrance so that we could put it in a small case that would be easily and comfortably wear without interfere with the athlete's movement.

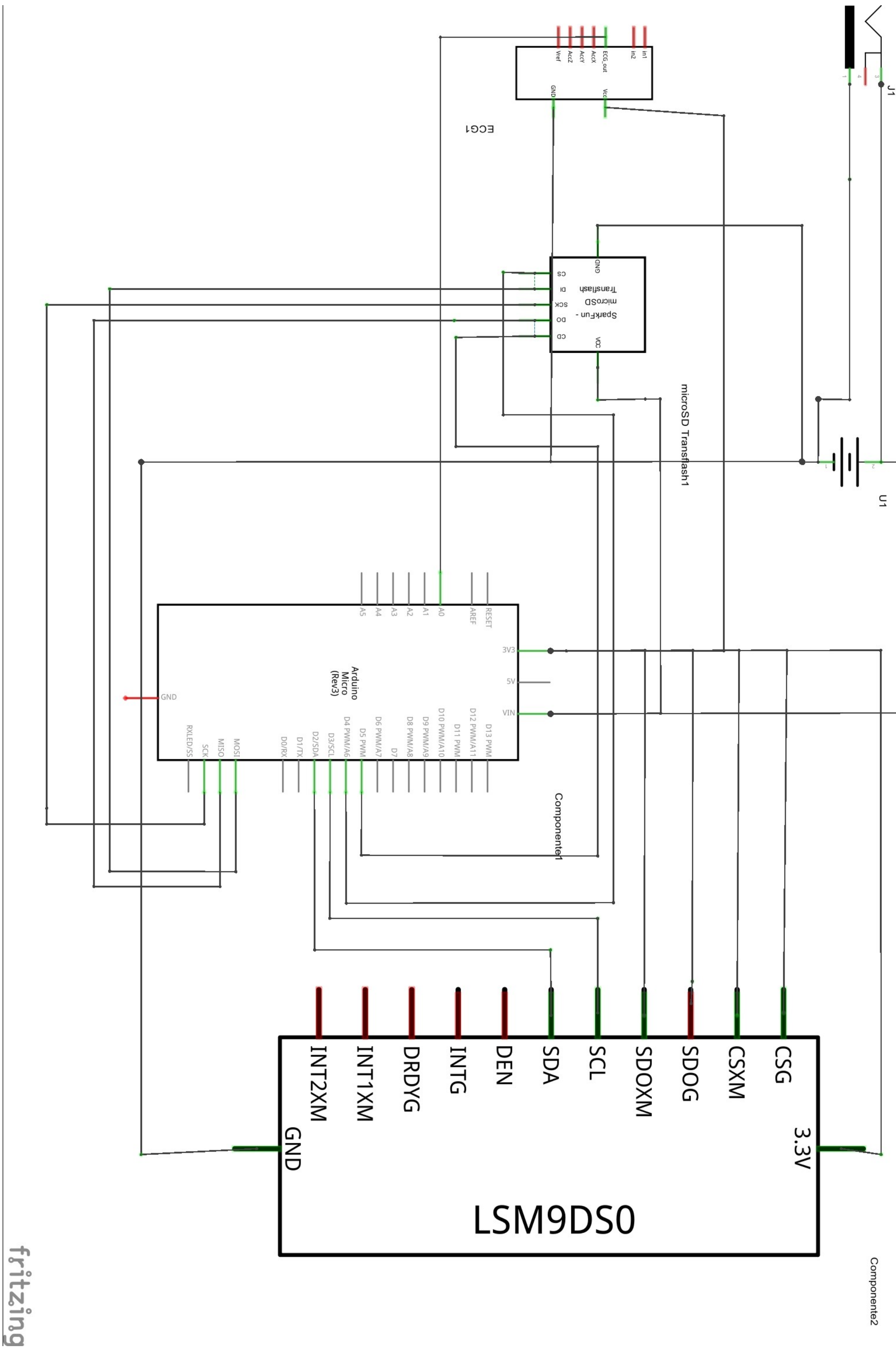

Figura 2.24: Scheme of the device's hardware.

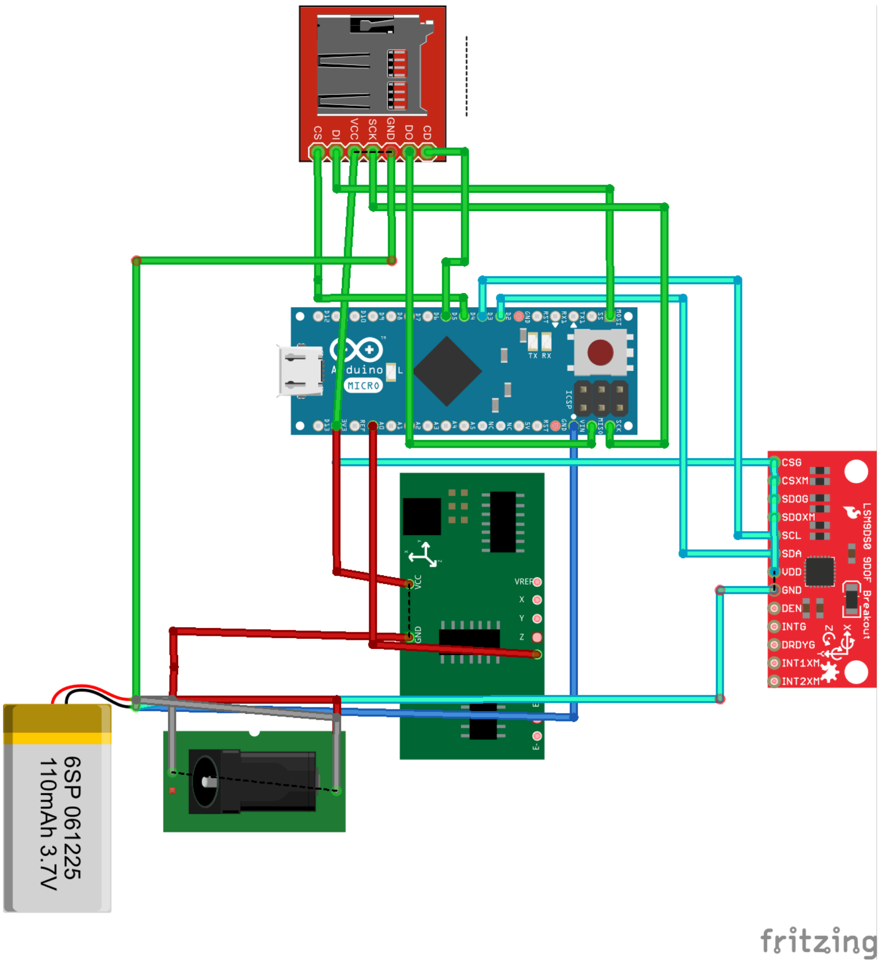

Figura 2.25: Scheme of the device's hardware: breadboard view.

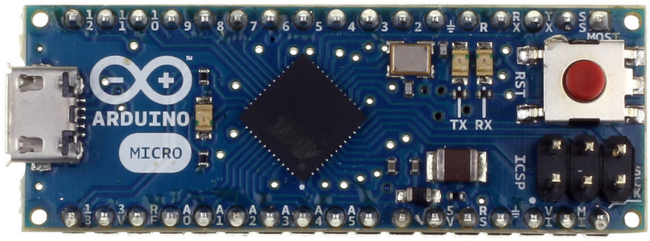

Figura 2.26: Arduino Micro: front view.

Inertial Measurement Block To collect data about the movement of the athlete, it has been chosen the 9 Degrees of Freedom IMU Breakout $LSM9DS0$ (Figura 2.27).

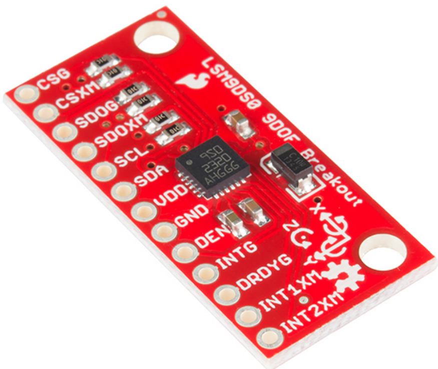

Figura 2.27: SparkFun 9 Degrees of Freedom IMU Breakout $LSM9DS0$: front view.

It is a motion sensing system in-a-chip that houses a 3-axis accelerometer, 3-axis gyroscope and a 3-axis magnetometer.

In this thesis' work we have only used information about acceleration however we considered to insert a IMU because, in a future perspective, it would be interesting understand if the integration of different information derived from different sensors can improve the device's performance.

The main future of the SparkFun 9 Degrees of Freedom IMU Breakout are synthesized in Tabella 2.17

ECG block This part has been realized by the Sensibilab group of Politecnico di Milano. The ECG block is composed by a first amplification

Acceleration Channels	3
Angular Rate Channels	3
Magnetic Field Channels	3
Linear Acceleration Full Scale	$\pm2/\pm4/\pm6/\pm8/\pm16g$
Gauss Magnetic Full Scale	$\pm2/\pm4/\pm8/\pm12g$
Angular Rate Full Scale	$\pm245/\pm500/\pm2000dps$
Data Output	16 bit
Serial Interfaces	SPI/I^2C
Analog Supply Voltage	$2.4V to 3.6V$
Other Specifications	Programmable interrupt generators Embedded self-test Embedded Temperature Sensor Embedded FIFO

Tabella 2.17: SparkFun 9 Degrees of Freedom IMU Breakout $LSM9DS0$: Main Features.

stage realized with an INA configuration. It keeps the signals derived from the two electrodes and has a gain amplitude factor of 6. In order to remove the offset (related to the DC component of the signal), it has been insert a low pass filter in the retroaction branch with the output connected with the INA Vref. In this way it has been realized an high pass filter with a cut off frequency of 0.15 Hz. Later the signal is filtered by a double filtering stages. The first one is a Sallen key low pass filter with a cut off frequency of 128 Hz. The second one is a anti-aliasing filter with a cut off frequency of 64 Hz. In this way it has been possible only to modify the cut off frequency of the second filtering stage, without changing the features of the first stage. Finally the signal is sent to the micro-controller and saved in the micro-SD.

Memory Block Sensors' data have been saved on a micro SD memory thanks to the SparkFun microSD transflash breakout.

Every data derived from sensors are then organized and saved as files *.csv* (comma separate values) on a microSD. The dimensions of this breakout board are really small so that it can occupy only few space.

Energy Supply Block This part of the circuit is made by:

1. Jack Connector: it is used to recharge the rechargeable battery;
2. Polymer Lithium Ion Battery;

The jack connector is the SparkFun Barrel Power Jack/Connector (Figura 2.29). It has a 5.5 mm jack with a 2.1 mm center pole diameter.

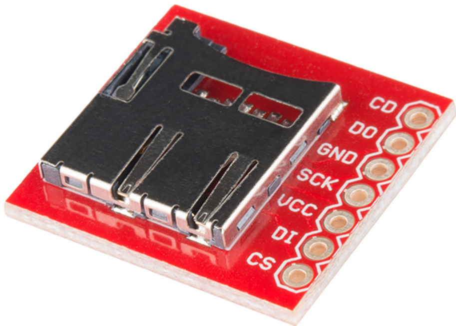

Figura 2.28: SparkFun MicroSD Transflash Breakout: front view.

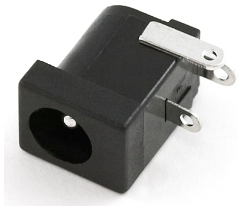

Figura 2.29: SparkFun DC Barrel Power Jack Connector : side view.

Its specifications are reported in Tabella 2.18

Rating	$16VDCat2.5A$
Contact Resistance	$30m\Omega max$
Insulation Resistance	$50M\Omega min100VDC$
Voltage Whistand	250V AC R.M.S. for 1 minute
Life	7000 cycles
Housing Material	PBT

Tabella 2.18: SparkFun DC Barrel Power Jack/Connector: Main Features.

The rechargeable battery is a SparkFun Lithium Ion Battery 110 mAh (Figura 2.30).

It is a very small and light weight battery and each cells outputs a nominal 3.7V at 110mAh. Its specifications are shown in Tabella 2.19.

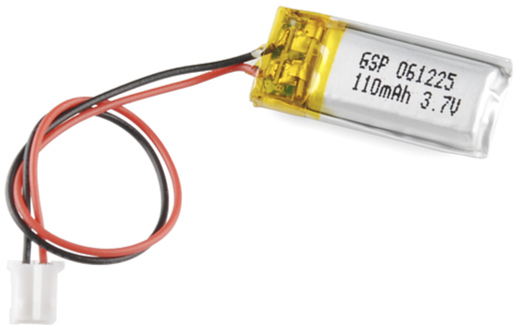

Figura 2.30: SparkFun Polymer Lithium Ion Battery-110mAh.

Dimensions	$5.7x12x28mm$
Weight	$2.65g$
Self Discharge Rates	$< 8\% permonth$
Nominal Capacity	100 mAh
Minimum Capacity	100 mAh
Nominal Voltage	$3.7V$
Cell Internal Impedance	$\leq 250m\Omega$

Tabella 2.19: SparkFun DC Barrel Power Jack/Connector: Main Features.

2.4 Software and Signal Processing

In this thesis work, the aim was to extract some interesting features only from the $3D$ accelerometer data given by the device. To comprehend which features can help the trainer and the athlete to analyze the sportive gesture, it has been studied the biomechanics of the movement and examined the state of art on this specific issue [21] [37] [39] [19] [17][38]. The Algorithm scheme is shown in Figura2.31.

Once we was aware of which indexes were useful to the swim technique evaluation, we started to concentrate ourselves in software development.

At first there was the need to understand which filtering it would have been useful applied to every signals (one acceleration signal for each axes) to eliminate noise's frequencies. It has been chosen to filter using the window technique and, in particular, a 64 samples Hamming window with a cut off frequency of 5 Hz. The cutoff frequency was suggested in literature [37]. Moreover, 'cause the algorithm is execute offline, we've chosen to use a phase zero filtering: in that way we could eliminate the linear delay introduced by

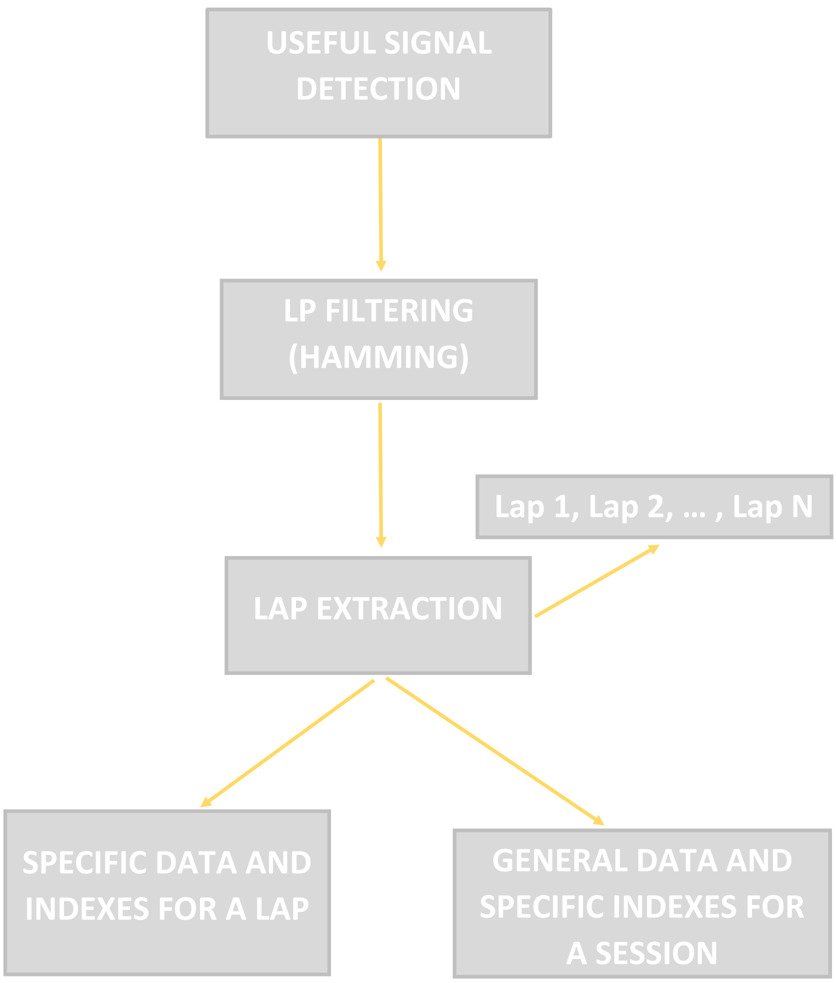

Figura 2.31: Scheme of the algorithm for the signal processing

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filtering data.

The first question to accomplish our aims, was in which way we could eliminate every samples representing movements not related with swim. It's very likely that a swimmer, after turning on the device, executes some movements, as walking or turn around his arms, that are registered by the accelerometer.

The intuition was to eliminate such part of the signal considering that they were over $-1g$ of magnitude in X-axis. As a matter of fact from an ideal point of view, when the swimmer changes his position from the vertical one to the horizontal one, the X axis sense has to be bigger than $-1g$ (if the X-axis is oriented along the movement axis). Furthermore we have considered that the signal has to be over the threshold for, at least 10 seconds (It is considered 10 seconds because the world short course record in 50 meters competition is about 20.26 for men[6]). It could be made the same, but opposite, deduction to comprehend, and state, where the end of the useful signal could be. The time in which the signal has to be, this time, less than $-1g$ is set arbitrarily at 7 seconds.

The next problem to solve had been to understand how we could divide the code in singular lap. At this point we asked ourselves which feature could discriminate between laps. Paying attention to the shape of every signal, it was decided to use the X acceleration signal. We can easily affirm, only observing the front crawl turn, that in each turn phase the swimmer push the wall causing the X acceleration signal to have a clear peak with a magnitude grater than that of the other samples. So, if we were able to detect these peaks, we could also understood where a lap ended and the next one began. Peaks were detected by using the *lapextraction* function. This function requires as inputs:

- A real vector from the maxima will be found;
- The amount above surrounding data for a peak to be indentified;
- A threshold value which peaks must be larger than to be maxima or smaller than to be minima;
- extrema: -1 if maxima are desired, otherwise -1 if minima are desired

In output it gives the indexes of the identified peaks and the magnitude of the identified peaks (Figura 2.33).

At this point we filled each lap vector with samples derived from the entire signal till we find the sample that has the same or less magnitude of the minimum peak between the previously identified peaks. When a peak is identified, the counter of the number of lap is incremented and the next lap begins to be filled with its samples. This cycle, implemented with a

[6] cfr. http://en.wikipedia.org/wiki/List_of_world_records_in_swimming

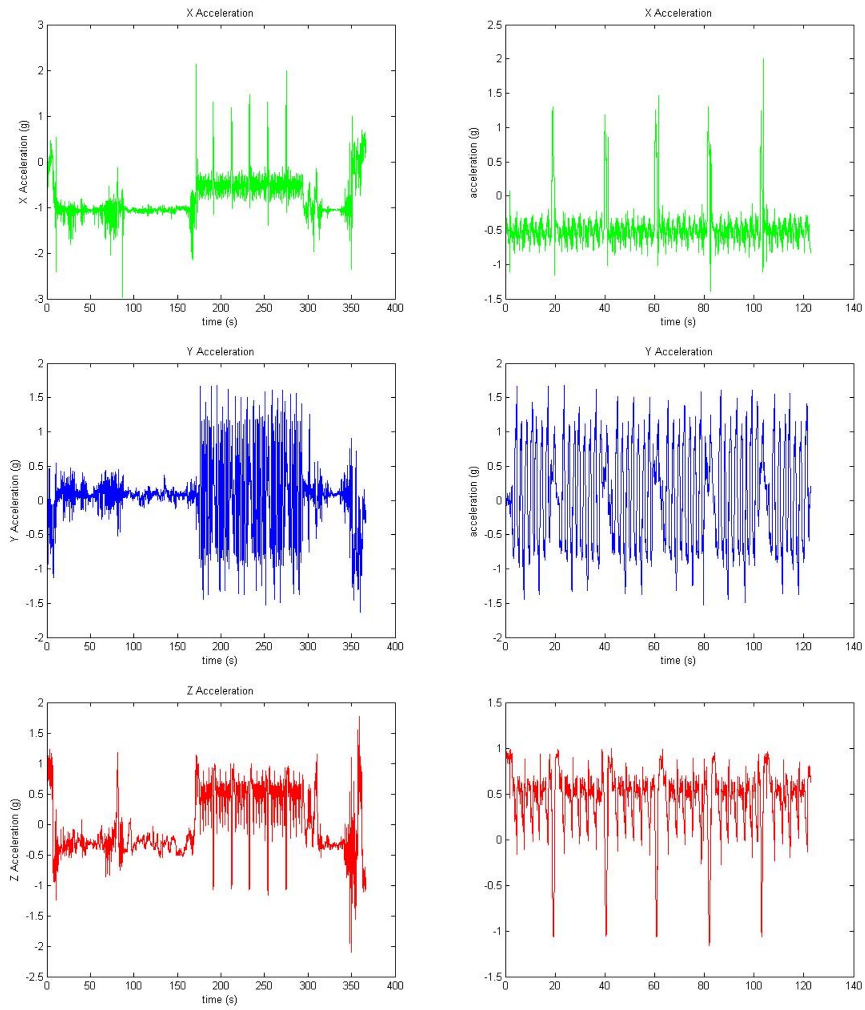


Figura 2.32: Useful signals extracted from the device output. Starting from the top we have the X acceleration, the Y acceleration and the Z acceleration.

while cycle, ended when the samples counter reach the exact length of the signal. Later the output was verified with the signal of the whole session (Figura 2.35).

Once we had information and data about each lap, we could calculate different indexes of the overall performance and of every laps. This is made possible through the creation of structure in which we can save several information and later display them to the user.

Number of strokes The Y acceleration signal obtained shows clearly a pseudo-periodical tendency. Each peaks represented an arm stroke so that,

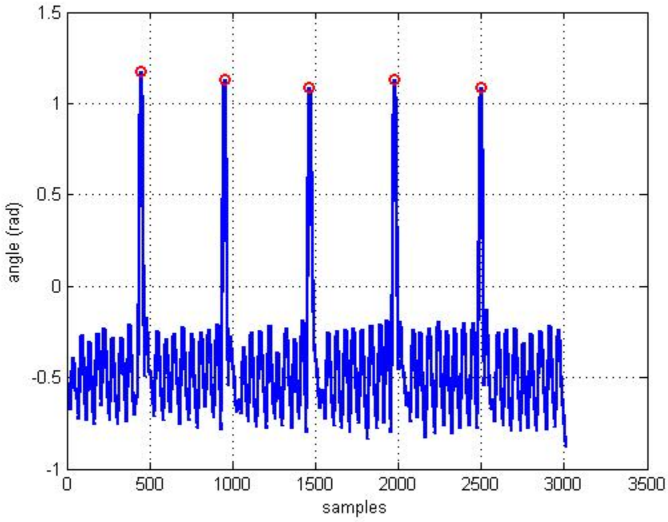


Figura 2.33: Peaks (push wall) of the X acceleration signal obtained with the peakfinder function

simply using once again the lap extraction function, after a filtering stage with a moving average filter with a window of $600ms$ (15 samples with a sampling frequency of 25 Hz) ,we can obtained not only the number of strokes, but also their amplitude. If we assume that the reference tern of the accelerometer coincides with that fixed of the pool as shown in Figura 2.38, a positive peak represented a right arm stroke and a negative peak represented a left arm stroke Figura 2.36.

Then we include some rules to verify if the peak is a real stroke or something else. If we are in the first lap are considered all peaks except for the last one if it appears in the last second (26 samples) before the turn. In this way we can prevent every movement made by the athlete to prepare himself to the turn. From the second to the last lap we add the condition that a peak is considered if it appears only after two seconds from turn so that we can exclude every movement made to return in the horizontal position after the wall push.

Finally, to extract the information about the number of strokes from data, we sum the number of left and right strokes to know how many strokes the swimmer has done in each lap.

Inversion Duration Because we can detect the first and the last stroke of a lap, we can also know the duration of the inversion by simply apply add the difference between the last sample of a lap and the sample representing the

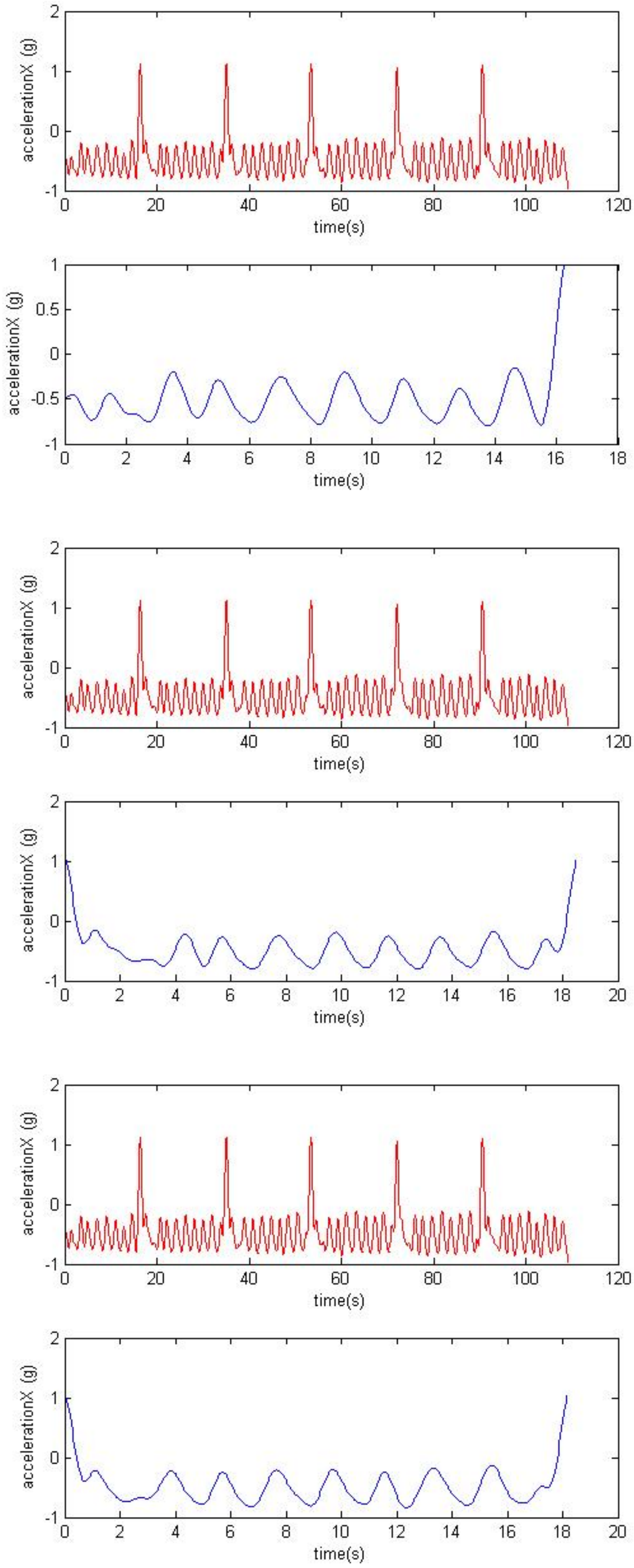


Figura 2.34: Lap division: example for the X axis acceleration. In this figure are shown respectively laps 1,2,3.

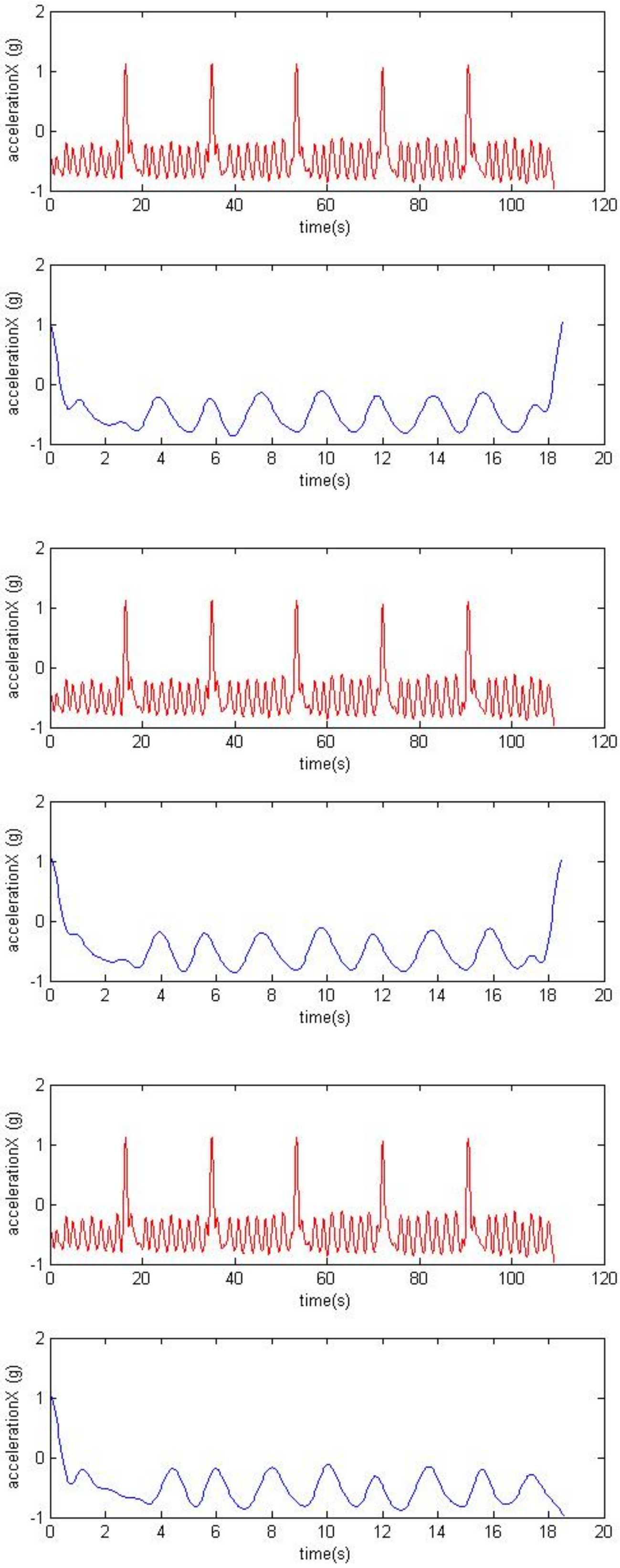
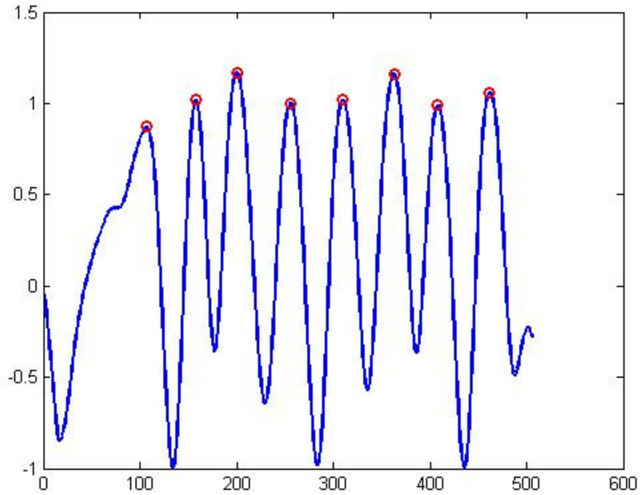


Figura 2.35: Lap division: example for the X axis acceleration. In this figure are shown respectively laps 4,5,6.



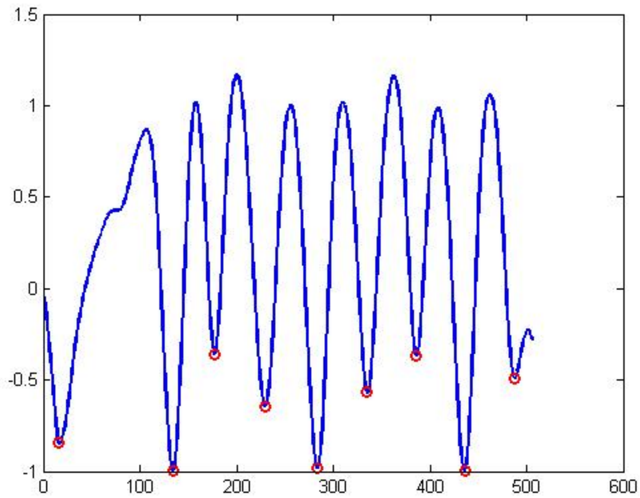


Figura 2.36: Strokes detection: positive peaks are right strokes and negative peaks are left strokes.

last stroke, and the samples of the next lap that represents the first stroke. This sum is later divided for the sampling frequency (Equation (2.1)).

$$ID = \frac{(s^i_{end} - s^i_{laststroke}) + (s^{i+1}_{firststroke})}{f_{sampling}} \quad (2.1)$$

Where s^i_{end} indicates the sample relative to the end of the i^{th} lap, $s^i_{laststroke}$ indicates the sample relative to the last stroke of the i^{th} lap, $s^{i+1}_{firststroke}$ is the sample relative to the first stroke in the $i^{th}+1$ lap and $f_{sampling}$ is the sampling frequency.

Time of each lap Knowing how many samples we have in each lap and the sampling frequency, we can calculate the lap time as the sum of the ratio between the length of lap data and the sampling frequency and an half of the inversion duration. Indeed, in this way, we consider also, from a theoretical point of wiew, the time spent to reach the wall (Equation (2.2)).

$$ToL = \frac{LoL}{f_{sampling}} \tag{2.2}$$

In this equation LoL represents the lap length, $f_{sampling}$ is the sampling frequency of the electronics and ID is the previous mentioned inversion duration.

Time per stroke In this case we only have to do a ratio of time of lap and number of strokes(Equation (2.3)). So we have information about the mean time spent for a stroke. The greater is the time, the lower is the number of stroke and the energy expenditure.

$$TpS = \frac{ToL}{NoS} \tag{2.3}$$

In this equation ToL is the lap time and NoS is the number of strokes.

Asymmetry Index This index give an idea of the asymmetry in magnitude of left and right strokes. We know, from the second Newton dynamic law, that the acceleration is related to the force generated. So if we found a method that relate the accelerations of every stroke we can have an index that represents the strokes disequilibrium. In this way we have another estimator for the energy expenditure of the athlete and it is obtain as the absolute value of the ratio between the magnitude of a stroke in respect to the previous one (Equation (2.4)).

$$AI(t) = |MagStrokeLeft(t)/MagStrokeRight(t-1)| \tag{2.4}$$

$MagStroke$ is the magnitude of respectively the left and right stroke.

At first we consider the first sample of this index equal to one (we surely have an odd number of left or right stroke). The second step is to consider the absolute ratio between the first samples in each stroke sequence (left and right strokes). Later we recognize which of the two sequences has the greater number of elements so that we can regulate the increment of the updating variable. In detail, when we have an even steps of the cycle we increment the index that moves along the greater vector on the contrary we increment the index that moves along the other vector.

The asymmetry index as a value that is greater or lower than one if the strokes are not so similar. So when we have a value far from one we have a strong asymmetry in stroke force.

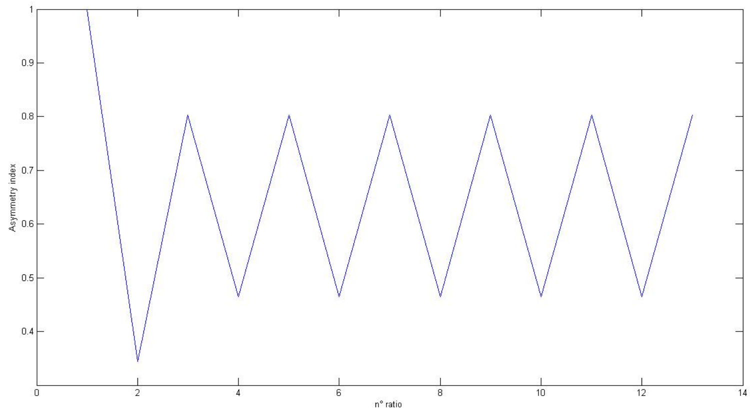


Figura 2.37: Asymmetry index for a particular lap.

Asymmetry Index Mean This is simply the mean of the value inside the Asymmetry Index vector (Equation (2.5)).

$$AIM = \frac{\sum a_i}{N} = \frac{AI}{N} \tag{2.5}$$

where a_i is the magnitude of the i^{th} sample inside the Asymmetry Index vector and N is the number of strokes in a lap.

This index summarize the mean asymmetry in magnitude between strokes so that we have an idea of the asymmetry in force during the lap between the left or right arm.

Stroke Variability Stroke Variability is an index that want to show if the swimmer has a regular stroke pattern or not. In other words it shows if an athlete has done strokes that cover approximately the same distance.

This index is defined as the relative standard deviation of the vector of distances (Equation (2.6)). So, in terms of percentage, we have the indication of the regularity of a swim pattern. The greater is the value, the greater is also the variability in the stroke pattern.

$$SV = \frac{\sigma_{distance}}{\mu_{distance}} \times 100\,\% \tag{2.6}$$

Where $\sigma_{distance}$ is the standard deviation of the distance vector and $\mu_{distance}$ is the mean value of every element inside the distance vector. First it is required the calculation of stroke distances vectors (distance between two following right and left strokes). Later we compute the relative standard deviation and the mean of values in distance vector, finally we make the ratio between the two obtained values.

Mean Distance Per Stroke Starting from the pool length (given by the user) and number of stroke, we can obtain this index showing the mean distance covered by each stroke (Equation (2.7)).

$$MDpS = \frac{l_{pool}}{NoS} \tag{2.7}$$

In this equation l_{pool} represents the pool length insert by the user and NoS is the number of strokes.

Mean Velocity The mean velocity is simply the ratio between pool length insert by the user and the time of lap previously obtained (Equation (2.8)).

$$v_{mean} = \frac{l_{pool}}{ToL} \tag{2.8}$$

In the previous equation shown, l_{pool} is the length of pool and ToL is the lap time.

Body Orientation Roll and pitch angles were calculated using what was described in USA patent *Real Time swimming monitor* [37]. These angles were defined starting from the neutral position of the swimmer shown in Figura 2.38.

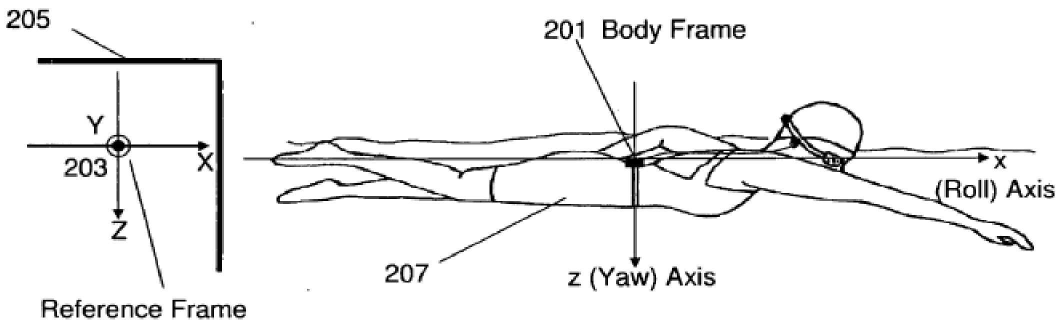


Figura 2.38: Neutral position of swimmer and reference tern.

In this way roll angle is defined as the angle formed by the Z axis of reference tern and the z axis of the tern that moves with the swimmer (Figura 2.39). Otherwise the pitch angle is defined as the angle formed by

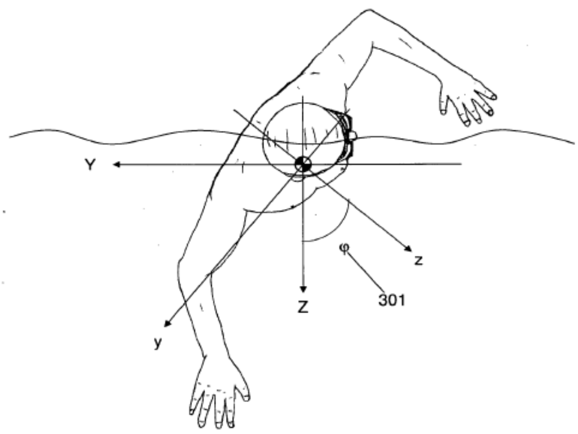


Figura 2.39: Roll Angle: definition

the relative positions of the two axis X and x during the athlete movement Figura 2.40. From an analytic point of view, these angles are calculated

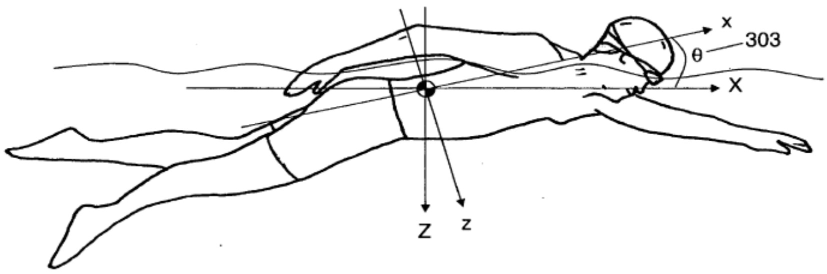


Figura 2.40: Pitch Angle: definition

starting from the Euleur theory. They can be obtain using the equations (2.9) (2.10) below:

$$\psi = \arctan(\frac{a_y}{a_z}) \tag{2.9}$$

$$\theta = \arctan(-\frac{a_x}{a_z}) \tag{2.10}$$

Where ψ is the roll angle, θ is the pitch angle and a_x, a_y, a_z are the three acceleration signals given by the three axial accelerometer. The signals where previously filtered with a moving average filter with a $600ms$ window (15 samples). Later we've subtracted the mean angle so that we can obtain the absolute angle formed by swimmers in respect to its neutral position.

The angles obtained are shown in Figura 2.41.

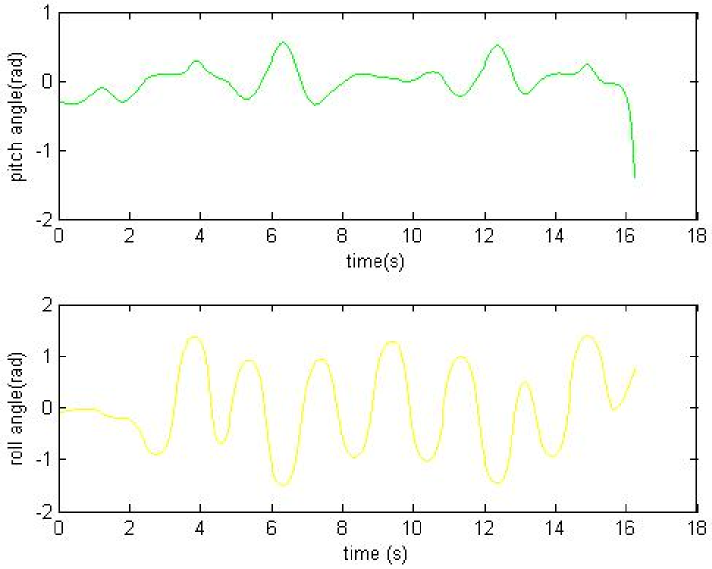


Figura 2.41: Pitch (green) and Roll (yellow) angle for a particular lap.

It was also obtained the mean pitch and roll angle of the athlete's body during the lap with the arithmetical mean method on the absolute value of angles magnitude (Equation (2.11)).

$$Pitch_{mean}(or Roll_{mean}) = \frac{\sum |\beta_i|}{N} \tag{2.11}$$

In this equation β_i represents the angles in pitch or roll vectors, and N the number of samples in vectors.

SWOLF SWOLF is an index derived from combining the terms swimming and golf because, as we know, in golf the less is the score the better is the performance. It considers the sum of the number of strokes and the time the athlete takes to swim a pool length (Equation (2.12)).

$$SWOLF = ToL + NoS \tag{2.12}$$

It is considered an indirect measure of swim efficiency . It is not an index that can be compared between swimmers, it is more meaningful in comparing different points of the same individual.

For example, if one obtains a score of 85 and later he can improve his performance changing his score in a lower one as 80, probably he has improved his efficiency because he can swim the same distance with a less number of stroke but trying to maintain the same timing.

Session Indexes Afterwards, because it is useful to have indexes related to the whole session, many of the previous data were also computed along the whole session. In particular they were all obtained, excepted for total time, using the equation below (Equation (2.14)):

$$Index_{session} = \frac{\sum index_i}{n_{laps}} \tag{2.13}$$

Wher $index_i$ is the specific index for a lap and n_{laps} is the total number of laps.

Contrarily total time is obtained by dividing the number of samples in signal for the sampling frequency.

$$ToS = \frac{n_samples}{f_samples} \tag{2.14}$$

In Tabella 2.20 are summarized swimming data obtained by the accelerometer signal processing:

Lap Indexes	**Session Indexes**
Time of each lap	Mean Time of Inversion
Number of Strokes	Mean Time of a Lap
Time per Stroke	Mean Time per Stroke
Asymmetry Index	Mean Stroke variability
Asymmetry Index Mean	Mean Session Distance per Stroke
Stroke Variability	Mean Velocity
Mean Distance per stroke	Total Time
Mean Velocity	Mean Pitch of Session
Inversion Duration	Mean Roll of Session
SWOLF	Mean SWOLF
Pitch	
Roll	
Pitch Mean	
Roll Mean	

Tabella 2.20: Indexes obtained by the signal processing of the accelerometer signals

To make possible a comparison between different laps, we have created graphical object in which It is possible to see the tendency of specific characteristics of the performance of the athlete. In Figura 2.42, Figura 2.43,Figura 2.44 and Figura 2.45 it is possible to see the whole plot created.

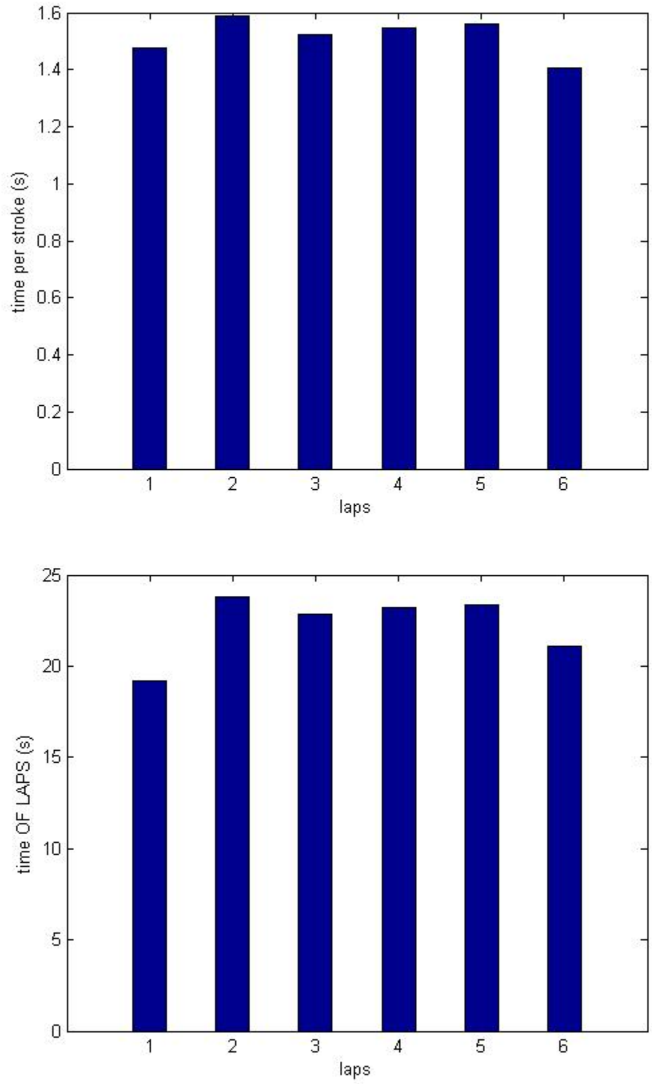


Figura 2.42: Plot of Indexes referring to a whole session. Starting from the top we can see Time per Stroke and Time of Lap.

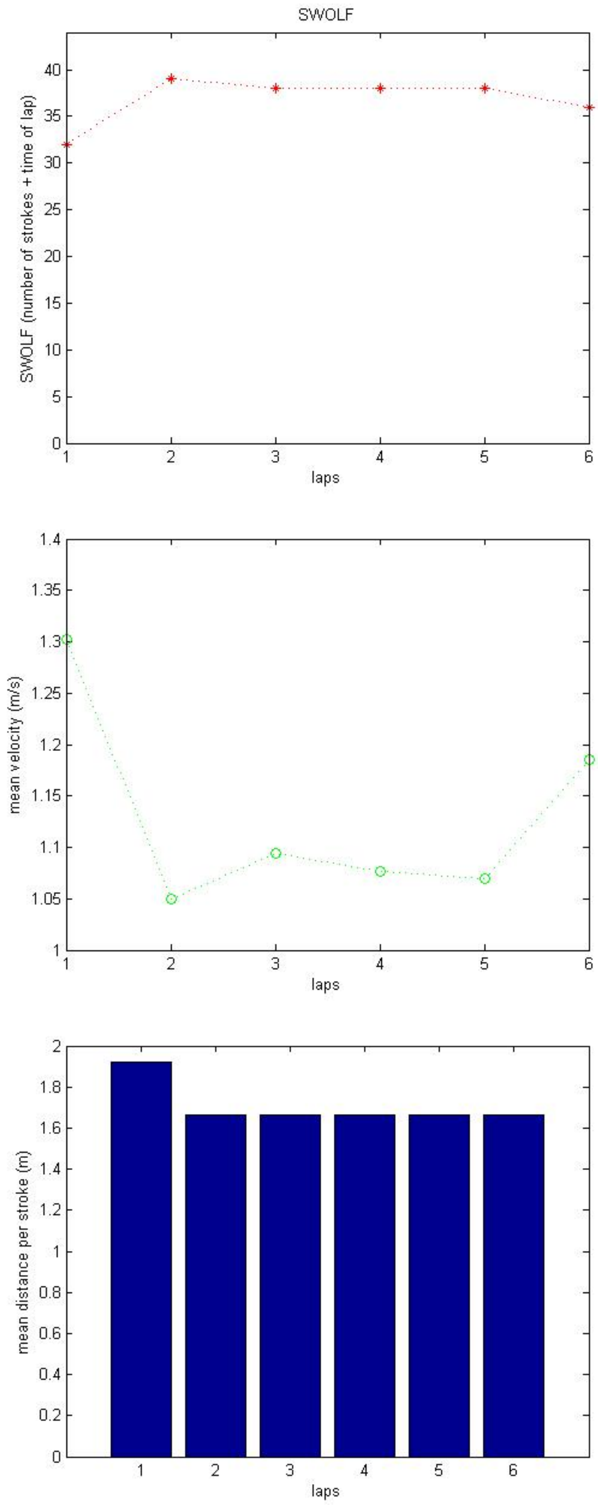


Figura 2.43: Plot of Indexes referring to a whole session. Starting from the top SWOLF, Mean Velocity and Mean Distance per Stroke.

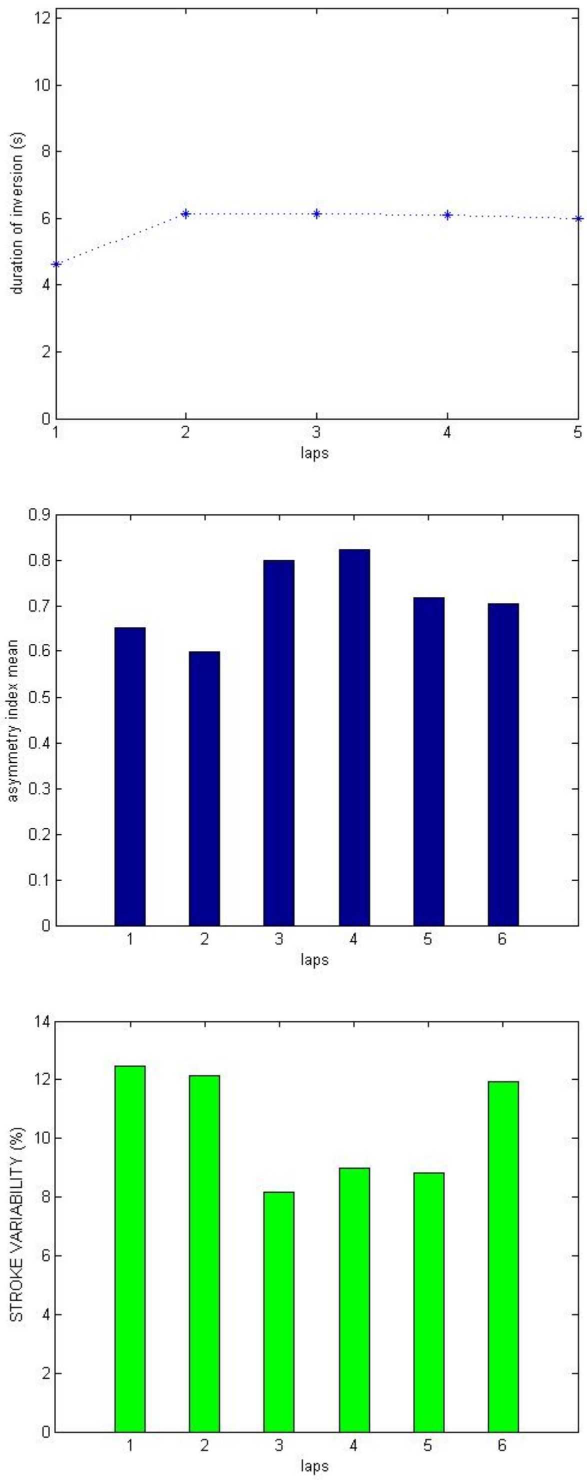


Figura 2.44: Plot of Indexes referring to a whole session. Starting from the top we can see Duration of Inversion, Asymmetry Index Mean and Stroke Variability.

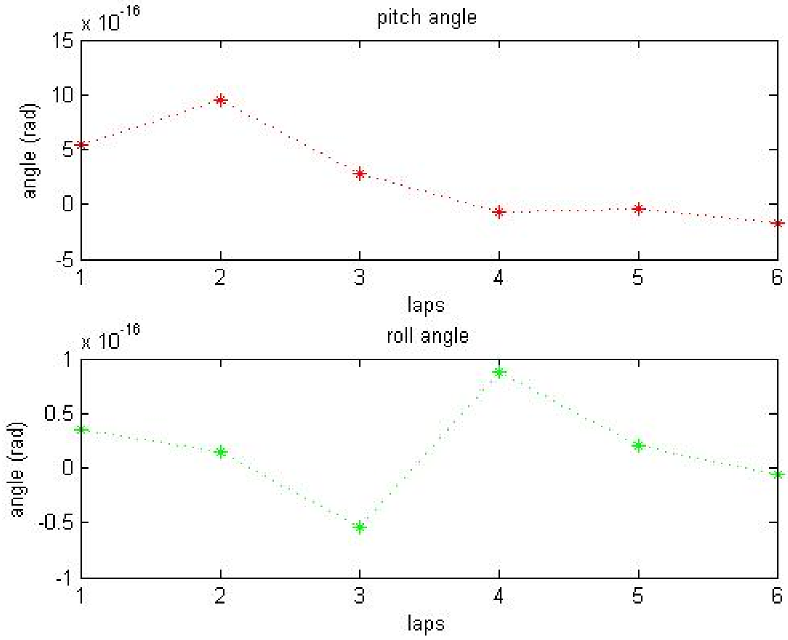


Figura 2.45: Plot of Indexes referring to a whole session: Mean Pitch and Roll Angle.

2.4.1 Development of a GUI with Matlab

Finally we tried to develop a user interface using the environment GUIDE (*Guided User Interface Development Editor*) offered by Matlab (Figura 2.46).

The GUI is composed by four sections:

- Selection of Lap: in this panel the user can insert the length of pool, choose which lap he wants to analyze and select graphs relative to the chosen lap;

- Indicies of Lap Performance: in this section the user can visualize the indicies relative to the lap selected in the specific panel;

- Indicies of session performance: here the user can select the graph he wants to analyze and see the global indicies referring to the whole session;

- Graphical Section: In this section the user can observe simultaneously the graphic information about one selected lap (shown in the lower graphical object called LAP) and about the whole session (shown in the upper graphical object called Session). This let the user to do

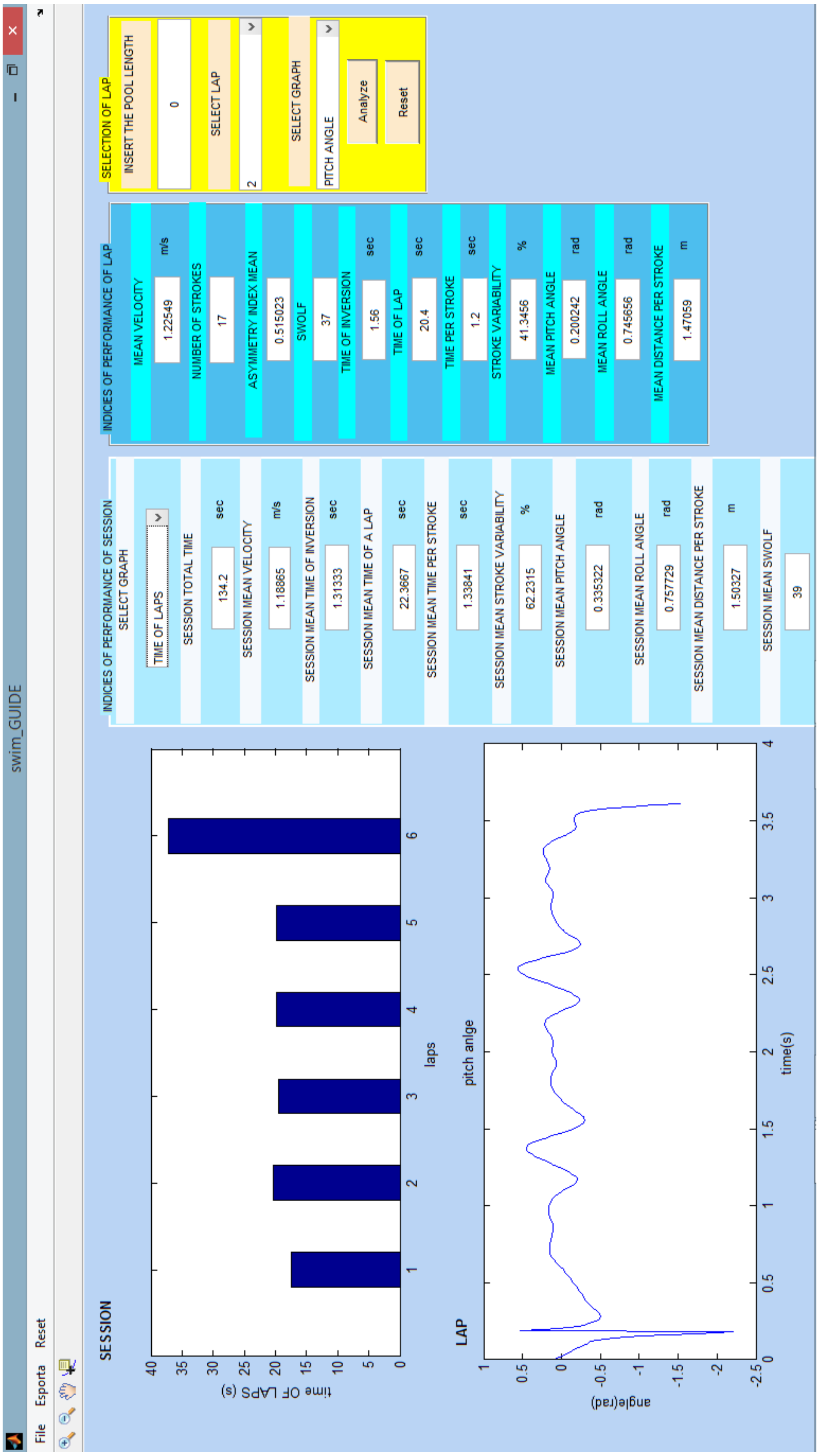


Figura 2.46: GUI created with the Matlab user interface development editor.

comparison and find which problem or where the athlete has more difficulties in the training session.

The first step required to the user is the insertion of the pool length in the apposite panel. If the user doesn't do this and go on in the use of the GUI, he will be warned by a specific text message (Figura 2.47) that he can't go further in using the application.

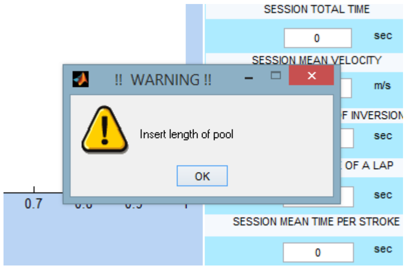


Figura 2.47: This warning message remembers to the user to insert the pool length.

Later he has to choose which data he wants to upload and analyze. It will be open a specific window in which the user can select between different training session Figura 2.48. It is possible to access to this function by pressing $Ctrl + O$ or press on file and select "*open*".

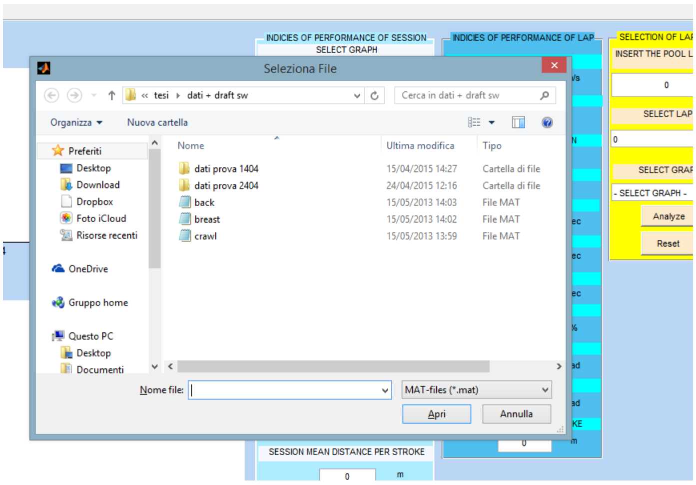


Figura 2.48: Selection of the data the user want to analyze. The window will open by pressing $Ctrl + O$ or selecting "file" and then "Open".

The data are then analyzed and subsequently indexes referring to the whole section appears on screen. At this point the user can select, by a specific pop up menu, which lap he wants to analyze and which graph he wants to observe.

It is also possible to export as an excel file the numeric data of the session. By clicking on the "*Esporta*" button or by pressing *Ctrl* + *E*, a window (Figura 2.49) will appear and the user has to insert different information about the athlete. This is of the utmost importance for the trainer who can compare different session and attest the improvement of his athletes. An example of report can be seen in Figura 2.50.

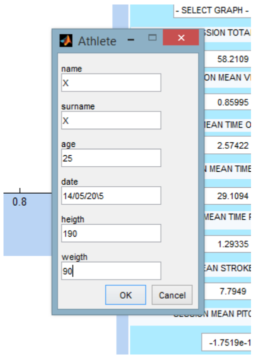


Figura 2.49: Info required as input when exporting data in Excel.

Whenever the user wants to clear the screen and restart from the beginning, he can push the button reset.

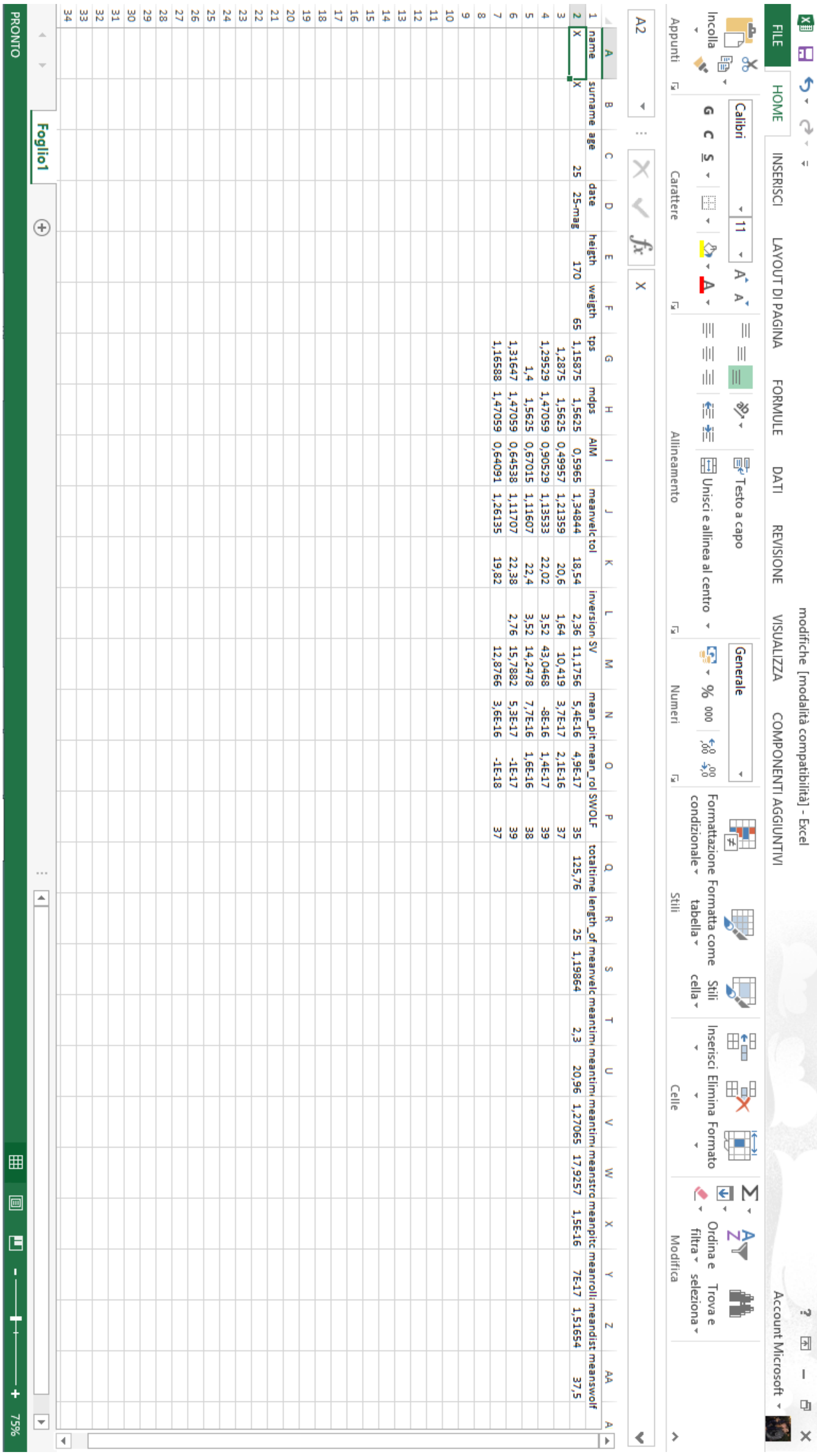


Figura 2.50: An example of Excel report obtained by pressing "Esporta" in the Swimming Gui and the window requiring the data of the athlete for the export of the report of the session.

Capitolo 3

Materials and Methods

3.1 Instrumentation and Setup for trials

3.1.1 Positioning of the Device

The project we are working on, consist in a wearable device placed on a swimsuit at a thoracic level.

Thinking on how to realize the validation trials setup, many were the problems encountered.

Firstly we was searching for a waterproof case in which we could insert the hardware. After many careful considerations, the model chosen was a waterproof for Mini DVR digital camera $MD80$ (Figura 3.1). In Tabella3.1 there are the case features.

Dimensions	$7cm \times 3.5cm \times 3cm$
Waterproof capacity	Up to 30 meters
Material	Plastic

Tabella 3.1: Features of DVR DV MD80 waterproof case.

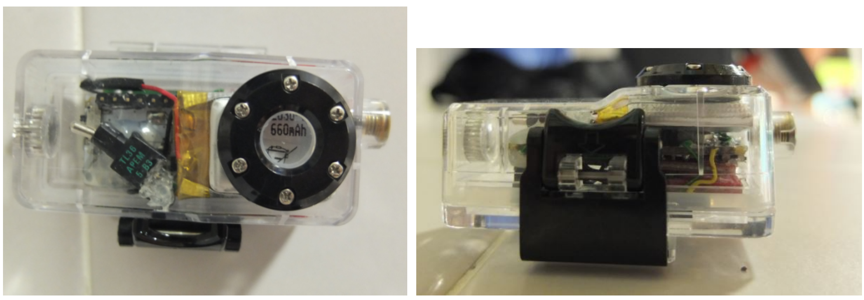


Figura 3.1: Waterproof case for the hardware.

With this case was sold also a bracket that let to wear it on a belt. So, at first, we thought it was possible to create an elastic chest belt (Figura 3.2) so that we could anchor the device on it.

Figura 3.2: Chest Belt for the device anchorage

It was created with an elastic band $1,15 meters$ length, on which pieces of velcro were seamed.

When we tested the setup, we comprehended that it was not a good choice. As a matter of fact, when the swimmer pushed the wall to begin the lap, the belt fell so that it wasn't no longer possible for the athlete to swim with the device. This is due mainly to the swimmers' body shape that generally is characterized by large shoulders and a thick pelvis. So it was necessary to search a more useful position and create a more stable support.

The idea was to directly create an elastic pocket on the swimsuit made of a material similar to the one used to realize the swimsuit. We decided that swimmers would wear a top in which we would have realized the previously mentioned pocket. The result is shown in Figura 3.3. Particularly we have chosen the Mikybee top made by Decathlon in three different size: medium for female athletes and large or extra large for male athletes.

In this case, during the setup's evaluation trials, there were no problem both in comfort and in undesired movement. Definitely it was opted for this last configuration.

3.1.2 Video: Structures and Cameras

Thinking to the trials and to the post evaluation of the indexes, arose the problem to understand in which way data would have been evaluated.

The first intuition was to use a simple videotaping of each trial so that it was simple to obtain, only with a visual feedback, information about strokes counting and swim's technique.

Subsequently we try to understand how many cameras would have been necessary to accomplish our aim . In order to have a complete feedback on the sportive gesture and thinking that some movements are hidden under the water surface, it was conclude that an optimal cams configuration had

Figura 3.3: Swimsuit with a pocket realized to contain the device.

to provide at least a double view: an underwater view and a view over the surface.

Furthermore, in addition to the lateral view, a more complete biomechanics evaluation can be obtain only with another point of view. In this way we would have also obtained a video data redundancy that can better support our results. The best configuration has been achieved with the positioning of two frontal/rear cams but we used only one, because the carry has a wide field of view and is able to record the whole pool length. Finally it was opted to use three cams: two of them would follow the swimmer and the other one would have been placed at one pool end. In particular the two moving cameras would have been placed respectively one on the surface of water and the other one underwater. In Tabella 3.2 are given to the reader the specifications about the positioning of the videotaping devices.

Number of cams	3
Positioning	1 moving underwater 1 moving on the surface 1 fixed at one end of the pool
Models	2 GoPro Hero 3 1 GoPro Hero 3+

Tabella 3.2: Cams specifications.

The next challenge was to comprehend how cameras would have been able to follow the swimmer. It was necessary a mobile structure on which it would have been possible to fix cams and that wouldn't have been so heavy to accomplish the aim of moving ourselves at the same speed of swimmers.

The first step was to buy a cart: we judged it was the best way to have at the same time a solid structure to support the weight of cameras and a moving structure that would have helped us, in a simply and low cost way, to follow the athlete during trials. It was opted for a folding cart Meister 9895619 (Figura 3.4) with a maximum carrying capacity of $150Kg$. The product specifications are described in Tabella 3.3.

Weight	$9Kg$
Dimensions	$54,6 \times 42,8 \times 12,2cm$
Maximum Load	$150Kg$

Tabella 3.3: Cart: product specifications.

Figura 3.4: Meister 9895619

Once we have had the cart, the problem was to build a structure able to support the cameras. Thanks to a great variability of mounts available, first it was established to use the handlebar mount (Figura 3.5). In particular it let us to clamp the GoPro cam to a roll bar with a small diameter tube (it fits $19.5to35.56mm$ tubes). Furthermore it has a $3 - way$ pivot arm offering a good adjustability in order to achieve the perfect angle for the videotaping.

Figura 3.5: GoPro Handlebar mount.

For the realization of the structure we use the elements shown in Tabella 3.4.

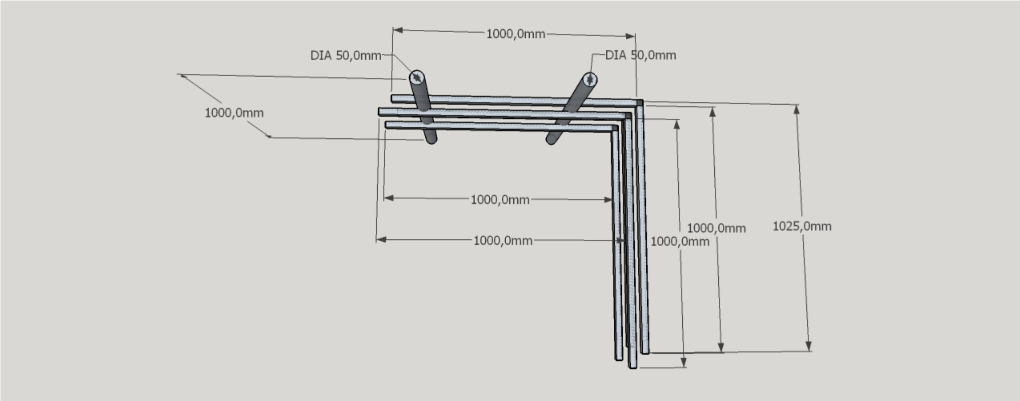
Component	**Quantity**
Aluminum cave tube with square basis 1m length and side of 2,5cm	8
Aluminum cave tube with round basis 1m length and 2,5cm diameter	2
Plastic connectors for squared tube	4

Tabella 3.4: Component for the structure realization.

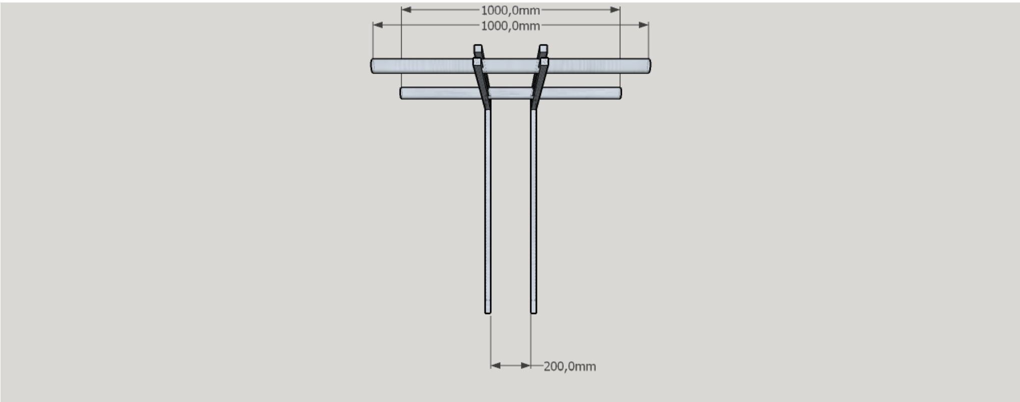
The project tables of the structure, realized using SketchUp, are shown in Figura 3.6 and in Figura 3.7.

Starting from the square tubes, it was necessary to create through-all holes for the bars' connection.More in details it was considered a hole of 13mm diameter.

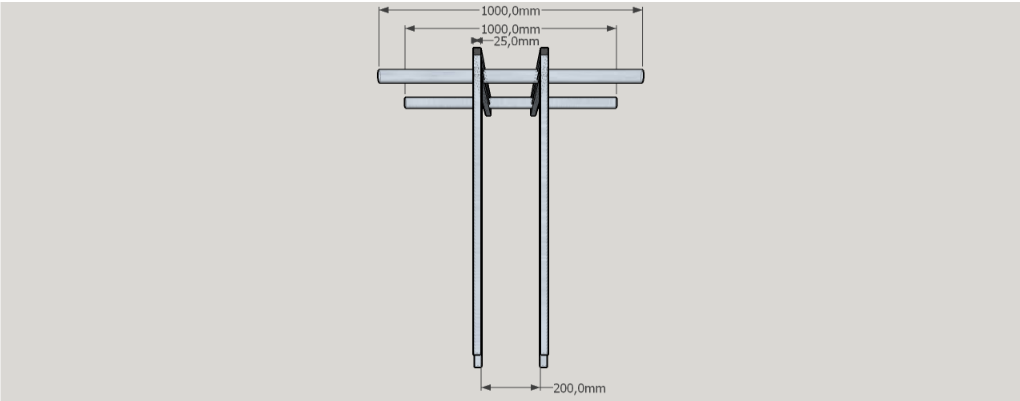
The structure designed needed to create an "L" shape with two tubes joined with the connector. Each horizontal part of the couple was assembled so that it could be anchored to the cart using a bolt-nut coupling. There were respectively an L-shaped structure on the upper surface of the cart and another one in the lower surface of the cart creating a sort of "sandwich" with the cart structure.



(a)

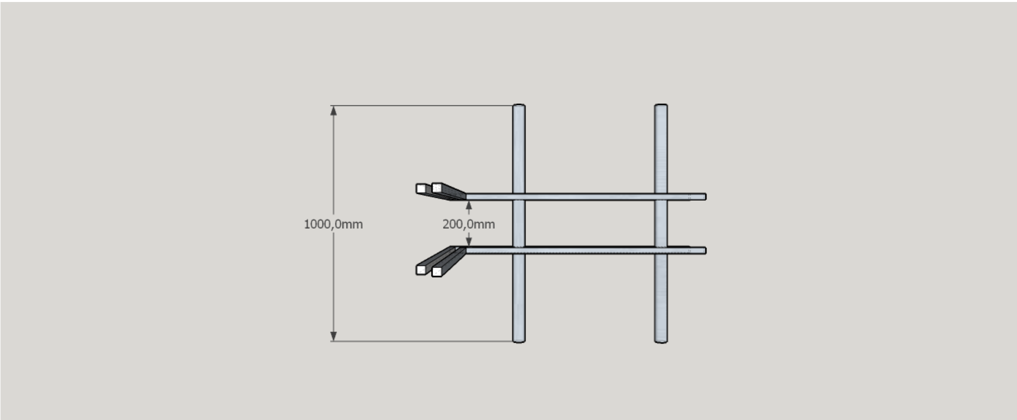


(b)

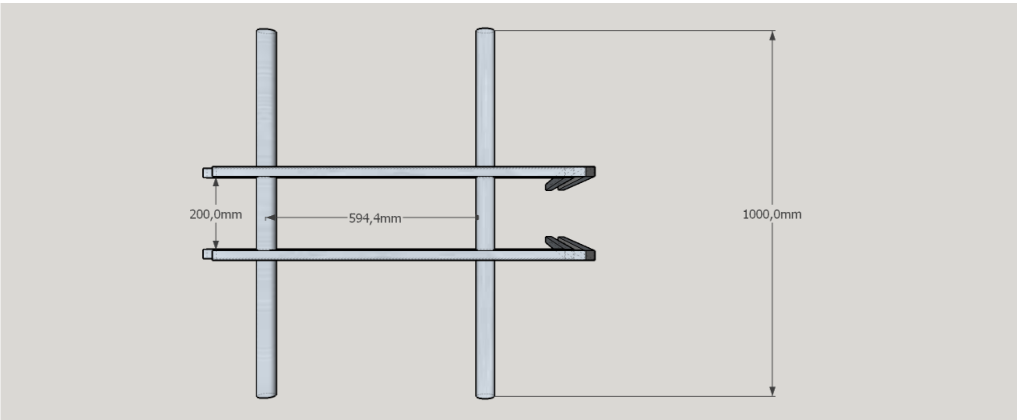


(c)

Figura 3.6: Different views of the structure project: in figure a) is shown the frontal view, in figure b) and c) are shown respectively the frontal and rear view.



(a)



(b)

Figura 3.7: Different views of the structure project:in figure a) and b) are shown the bottom and the overhand view.

These two L-shaped structures had to be out of line thus creating a space of about $2,5cm$ with the aim to insert between them the two round tubes. It was necessary that, in each vertical part of the L-shaped structures, the holes would have been in correspondence with the ones created on the round tubes.

The round tubes was positioned horizontally and perpendicularly in respect to the vertical square tube. These tubes had the same features of common handlebars thus they was compatible with the required dimensions for GoPro mounts.

The distance between two round bars was tested and later fixed at $60cm$. Nevertheless there was the possibility to change the distance thanks to other holes made in the planning stage Figura 3.8.

Figura 3.8: Positioning of the cam on the round tube with the GoPro mount.

At first, the lengths were not changed but, during the setup evaluation trials, we realized that the structure had opposed a huge resistance to its movement. This was due mainly to the presence of water. Then we cut the vertical tubes of the L-shaped structure to a length of about $70cm$ and the round tubes to a length of about $50cm$. In this way we obtained a reduction of structure resistance.

The structure is shown in Figura 3.9.

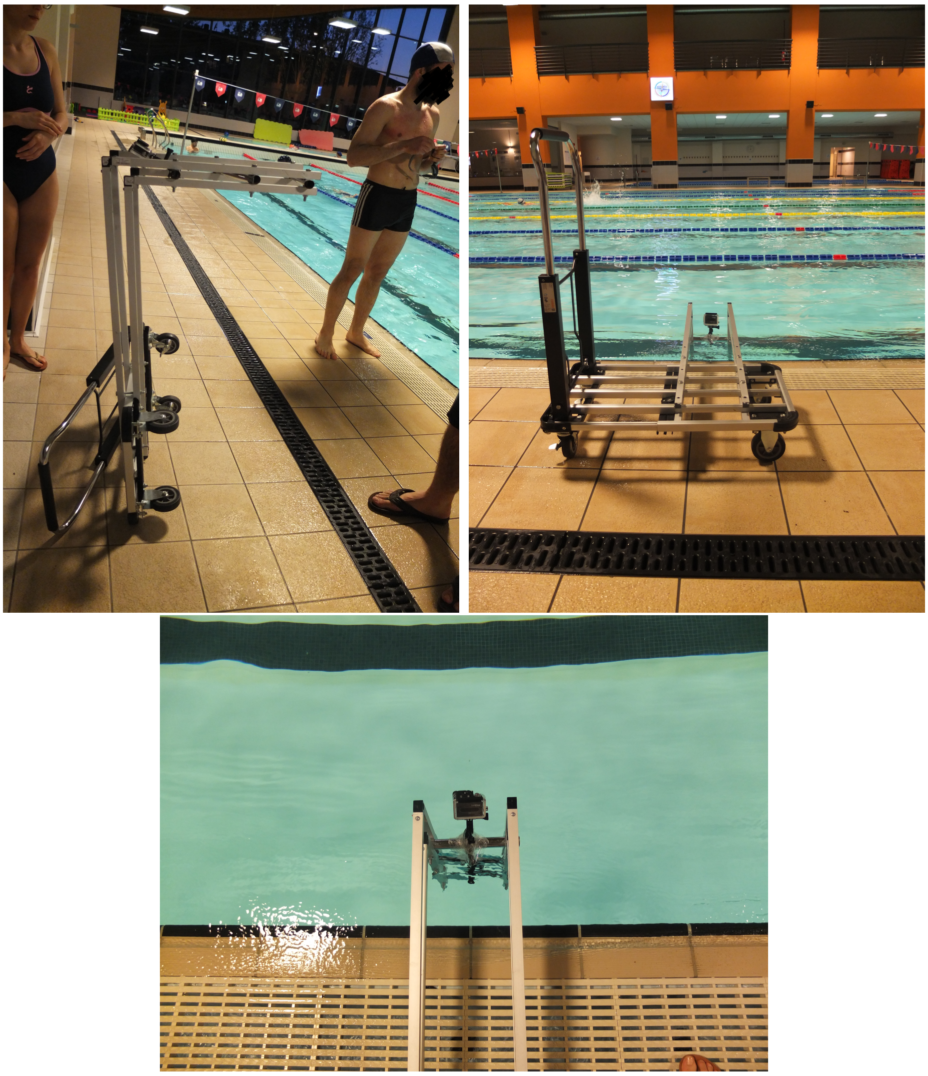


Figura 3.9: Cart structure for trials video-recording.

3.2 Validation Protocol

The validation protocol was thought in order to evaluate the accuracy of the software and to better understand its limits. Furthermore some trials were specifically designed to a possible improvement of the software and of the signal processing phase.

Subjects	Proficiency and non proficiency
Age	24 – 60
Gender	7 M and 3 F
Anthropometric data	No restrictions

Tabella 3.5: Subjects for Trials

3.2.1 Subjects

In Tabella 3.5 are shown the characteristics of subjects underwent to the validation trials.

It was decided to test both pros and non pros subjects with an age within 18 and 60 years old. For pros athlete we consider a person who has more than 5 years of experience in a professional level. This choice was made for two main reasons:

- Pros subjects can swim different styles with a high level of ability so that the features of signals derived by the accelerometer are nearest to the ideal one;
- Non pros subjects help us become aware if the device would have replied also in case of a non perfect technique, thus giving a realistic response also with non ideal signals.

Furthermore we decided to take note of anthropometric data of athletes so that we would have the opportunity to observe also some eventual tendencies of the device in respect with gender, age, weight or high. Nevertheless there are no restrictions in respect with this data because every gender, height or size doesn't affect the normal functioning of this device and these data are not influential from a statistic point of view.

3.2.2 Trials

In the planning phase of trials, it was considered to analyze each style in the same way. We can distinguish between two different kind of trials:

1. Validation trials;
2. Data collection for the signal processing improvement.

In Tabella3.6 are described the conditions and the set up thought for the validation trials.

The goal of these trials (Figura 3.10) was that of to have some data to submit to the algorithm so that we would have attested, with a comparison between trainers data and the software output, if the device was able to furnish real and objective data.

Device positioning	Standard (*thoraciclevel*)
Laps	3
Video recording	3 go pro cams 2 moving cams on cart and one fixed at one pool end
Requests	The trainer or an operator has to keep trace of time using a chronometer

Tabella 3.6: Validation Trials Protocol

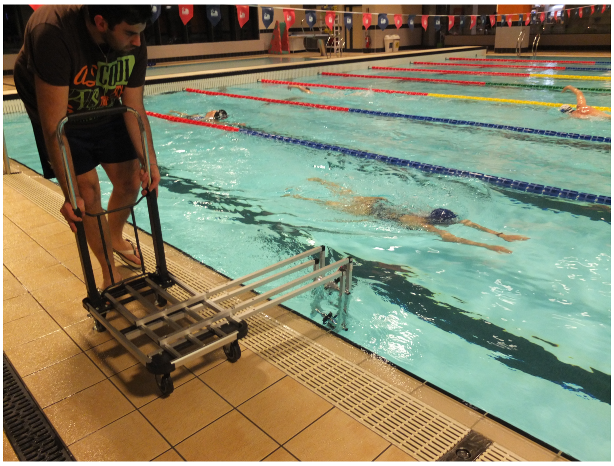


Figura 3.10: Validation trials.

Many were the questions that have arisen during the development of the algorithms. Thus the best way to give evidence to such ideas was to create specific protocols to obtain data to confirm such hypothesis. The first problem we faced with was to understand if it was possible to extrapolate kicks movement from the signal obtained positioning the device in thoracic zone. In Tabella 3.7 there are the specifications for this kind of trials.

Given that the position of the device was far from the source of the movement (lower limbs), we thought to bring it nearer to the legs so that the signal would have been obtained the more higher as possible. This could have let us to understand if a similar pattern, achieved from this particular position and considered as a archetype of limbs movement, would have been present also in the signal obtained at thoracic level. This hypothesis came from consider that the human skeleton is a jointed structure and that something about legs movement can be observed also at an upper level.

Device positioning	At sacrum level
Laps	1 Normal + 1 overdoing movement
Video recording	3 go pro cams 2 moving cams on cart and one fixed at one pool end
Requests	The movement has to be done with the use of a kick board (only lower limb movement).

Tabella 3.7: Kick Movement Trials Protocol

This sort of trials would have been made also to evaluate how the indexes of asymmetry would have responded (Tabella 3.8). These trials offer also

Device positioning	Standard
Laps	2 accentuating the imbalance
Video recording	3 go pro cams 2 moving cams on cart and one fixed at one pool end

Tabella 3.8: Imbalance Trials Protocol

the opportunity to better understand how and in which way the algorithms would have shown us the asymmetry of the movement and if this indicator would have been useful for our purposes. These trials could have been applied, with some corrections, to every swim style.

3.3 Video post processing: GoPro Studio

GoPro studio is a software licensed by GoPro (Figura 3.11) that help us to provide annotations and analyze video documents. It can also give us the opportunity of having a precision of cents of seconds: this is very important for the assessment of the algorithm performance. Indeed, in sports like swim, it is of the utmost importance have a feedback with the highest precision possible.

By using it, we can do a sort of post-processing of video data, and then recognize some features, as lap times and number of arm strokes, and compare the results given by the device with the information extracted from the video's analysis.

Furthermore we can have, undoubtedly, an objective comparison between the software algorithms' data and video data. In this way the device's validation is not affected by intra-operator and inter-operator variability in collecting data.

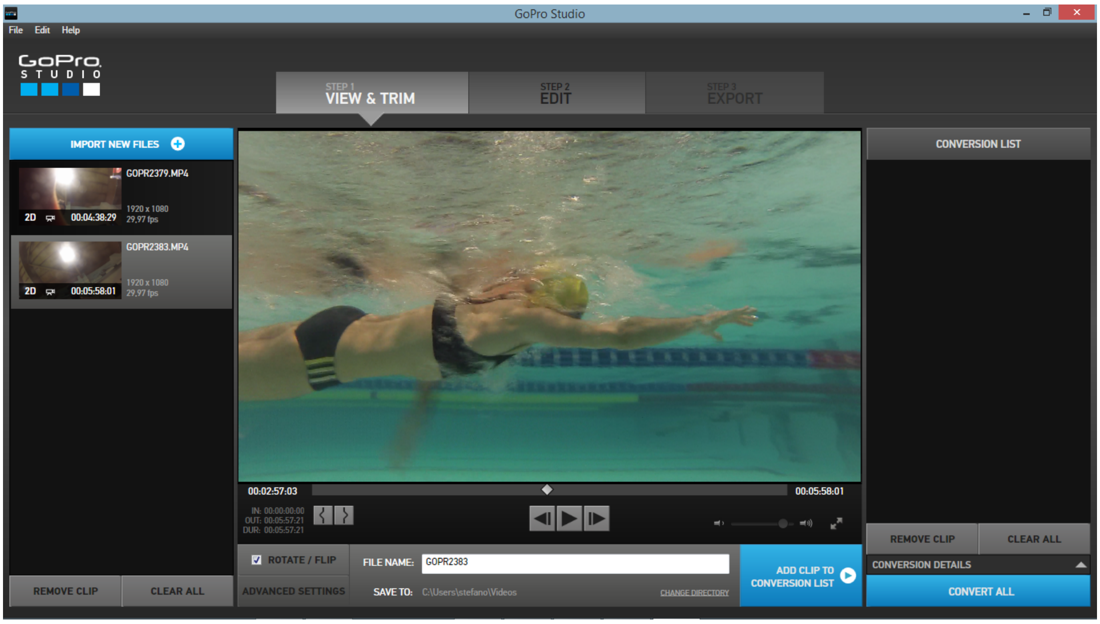


Figura 3.11: GoPro Studio: software user interface.

3.4 Statistical Indicators and Methodologies

The methodology used for the algorithm evaluation is based on the comparison between data obtained with video processing and data obtain with the use of the algorithm. In particular we will consider only lap time, inversion duration, number of lap and number of strokes because most of the indexes refers to these indicators. Furthermore it will be compute the error made by the operator that took note about lap time so that it will be possible to compare algorithm data and operator data in order to asses which one obtains the best results or if they have approximately the same results.

For each data it will be computed the absolute error defined as:

$$err_i^j = x_{mis} - x_{real}$$

where err_i^j is the error j of the indicator i .

In this way we will obtain, for each indicators, a series of errors.

Then we will simply compute the mean error and the standard deviation of the distribution of errors.

Deviation standard and mean are obtained as below:

$$\mu_j = \frac{\sum err_i^j}{n_{err}}$$

$$\sigma_j = \sqrt{\frac{\sum((err_i^j - \mu)^2}{n-1}}$$

where μ_j is the mean and σ_j the standard deviation of errors of the relative indicator j.

Then it will be possible to comprehend if the errors will be smaller than we expect or not, and evaluate if these errors can be accepted or not.

Considering the number of strokes, errors will be computed as the percentage of the number of strokes lost compared to the whole strokes in the lap.

$$Err_{NoS}\% = \frac{NoS_{lost}}{\sum NoS_{lap}}$$

It will be also computed the mean percentage errors for each trial and then compared with that computed for the other trials.

Finally it will be obtain also a sort of "*Stroke Sensitivity* ": in this way it would be clear the response of the algorithm in the identification of strokes. About this, it has been created, with the help of my tutor, a specific GUI Figura 3.12 in which it is possible to synchronize acceleration data and video data. In this way it would be possible to asses if the stroke recognized by the algorithm is a real stroke or another movement.

Using this GUI we can obtain the number of TP (true positive), defined as the strokes detected by the algorithm that are real strokes, and FN (False Negative), defined as the strokes not detected by the algorithm but that the athlete has done. Later the stroke sensitivity is computed as below:

$$Sensitivity\% = \frac{TP}{TP + FN} \times 100$$

Later, dividing the sum of the percentage values for the number of trials, will be obtain the mean percentage sensitivity.

At the end of this analysis it will be clear if the software is ready to be used or it requires other necessary improvements with the aim of guarantee its reliability.

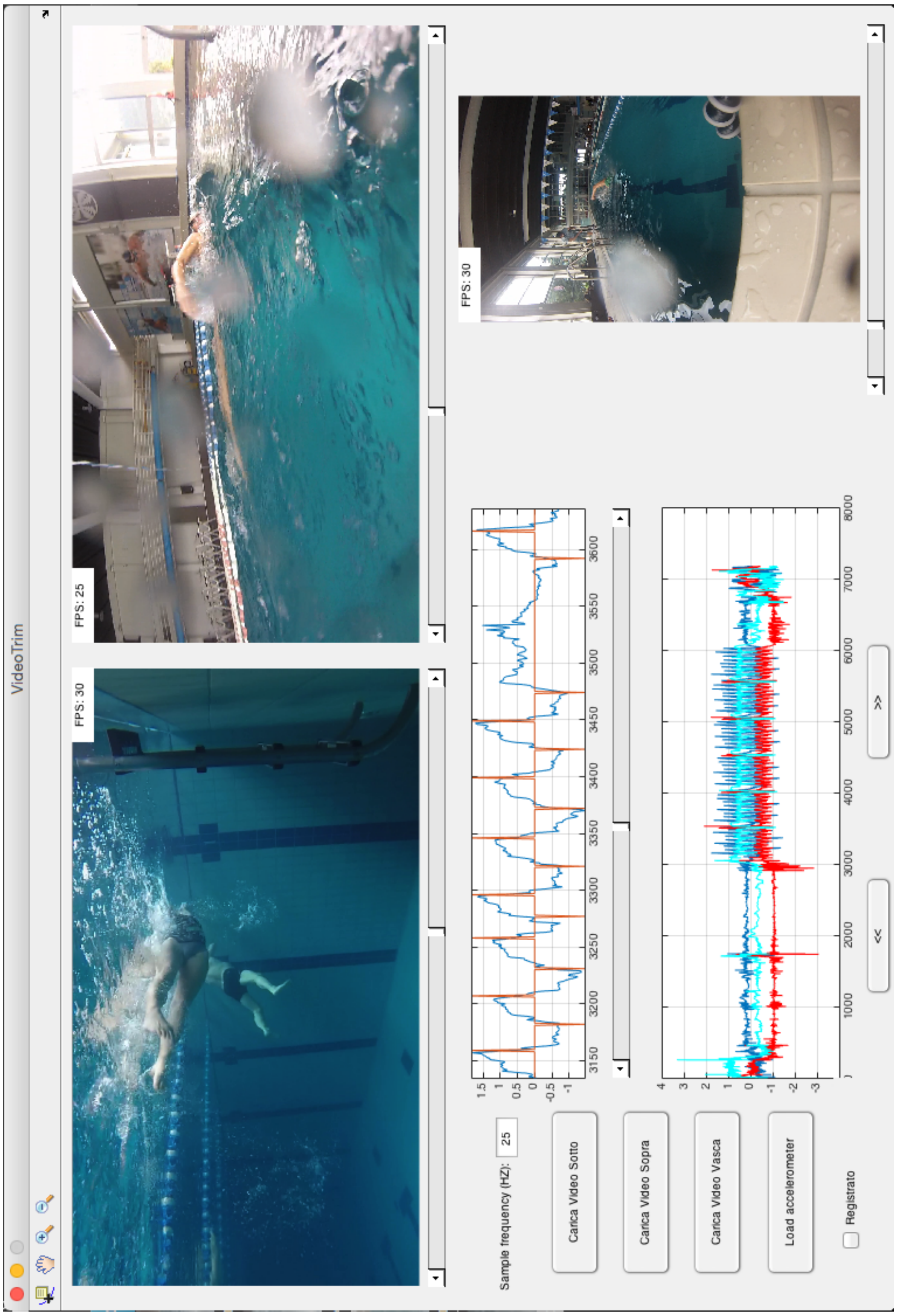


Figura 3.12: GUI realized with Matlab for the Stroke Sensitivity assessment. It is possible to upload accelerometer data and video data in order to synchronize the signals and understand if the strokes are real strokes or other movements.

Capitolo 4

Device's Validation

4.1 Results

In order to evaluate the device's performances, we have analyzed 13 trials from different subjects. Unfortunately, trials on amateur swimmers were not considered because, during these sessions, the device didn't work and gave us not reliable data.

In particular we can distinguish two trials' sessions. The first one was made in Pratogrande swimming pool of Lecco. The second one was made in collaboration with Seven Infinity sport center in Gorgonzola.

During these session we decided not to follow the whole protocol. Given that we didn't have the time needed, we decided to focus on the front crawl technique and let the athlete choose how many laps he wanted to execute. In this way we would have tested also the reactivity of the algorithm in lap division. This was made in order to accomplish our aim of testing and validate the algorithm, and, for the time being, not deal with the device performance improvements.

In this section are reported only records useful to the evaluation of the algorithm.

4.1.1 First Session: Pratogrande Lecco

The first session was made with a female pro-athlete whose information are reported in Tabella 4.1.

Name	V.
Surname	V.
Gender	Female
Age	43
Level	High (about 35 years)

Tabella 4.1: First Athlete: general features.

We asked her to complete six laps with a medium speed. The last request was made in order to let us follow her with the cart without any problem. She has done in total four trials and results for each trials are shown below.

First Trial

The algorithm outputs of the first trial are shown in Tabella 4.2.

indexes/lap	lap1	lap2	lap3	lap4	lap5	lap6
Nos	15	15	15	16	15	19
ToL (s)	19, 52	20, 24	19, 88	20, 64	20, 04	35, 8
ID (s)	4, 88	5, 6	5, 76	6, 52	5, 36	
Number of laps:	6					

Tabella 4.2: Algorithm Results: first trial.

The data obtained by the video analysis are reported in Tabella 4.3.

indexes/lap	lap1	lap2	lap3	lap4	lap5	lap6
Nos	14	15	15	16	15	16
ToL (s)	19, 8	19, 87	19.72	20, 56	19, 79	19, 32
ID (s)	4, 82	6	5, 07	5, 79	5, 18	
Number of laps:	6					

Tabella 4.3: Video Results: first trial.

Time of laps data obtained by the operator are shown in Tabella 4.4

The error found with the comparison between algorithm and video data are shown in Tabella 4.5.

As we can see from tabs, the errors in number of strokes is of one stroke in the first lap and three strokes in the last one. From the tables, the

index/lap	lap1	lap2	lap3	lap4	lap5	lap6
ToL Operator (s)	20	21	20	20	20	20

Tabella 4.4: Time of Lap given by the operator.

indexes/lap	lap1	lap2	lap3	lap4	lap5	lap6
err_{Nos}	1	0	0	0	0	3
err_{ToL} (s)	$-0,28$	$0,37$	$0,16$	$0,08$	$0,25$	$16,48$
$err_{ToLOperator}$ (s)	$0,2$	$1,13$	$0,28$	$-0,56$	$0,21$	$0,68$
err_{ID} (s)	$0,06$	-0.4	0.69	$0,73$	$0,18$	
$err_{Numberoflaps}$:	0					

Tabella 4.5: First Trial Error. In yellow are underlined cells with the max error value.

maximum error given by the algorithm in lap time, is about $16,28s$ in the last lap.The maximum error in inversion duration is $0,73s$ in the fourth inversion. Furthermore all the laps are recognized thus the relative error is equal to zero. Talking about the errors made by the operator, the maximum one is of $1,13s$ while, the others, remained under one second.

Second Trial

The algorithm outputs of the second trial are shown in Tabella 4.6.

indexes/lap	lap1	lap2	lap3	lap4	lap5	lap6
Nos	15	16	16	16	16	16
ToL (s)	$17,76$	$19,96$	$20,44$	$20,36$	$20,72$	$20,36$
ID (s)	$5,6$	$5,36$	5	5	$4,88$	
Number of laps:	6					

Tabella 4.6: Algorithm Results: second trial.

The data obtained with the video analysis are reported in Tabella 4.7.

indexes/lap	lap1	lap2	lap3	lap4	lap5	lap6
Nos	15	16	16	16	16	16
ToL (s)	$18,91$	$20,3$	$19,99$	$20,4$	$20,15$	$20,3$
ID (s)	$5,32$	$5,56$	$5,5$	$4,26$	$5,27$	
Number of laps:	6					

Tabella 4.7: Video Results: second trial.

Time of laps data obtained by the operator are shown in Tabella4.8

index/lap	lap1	lap2	lap3	lap4	lap5	lap6
ToL Operator (s)	19	21	21	18	21	20

Tabella 4.8: Time of Lap given by the operator.

The error found with the comparison between algorithm and video data are shown in Tabella 4.9.

indexes/lap	lap1	lap2	lap3	lap4	lap5	lap6
err_{Nos}	0	0	0	0	0	0
err_{ToL} (s)	$-1,15$	$-0,34$	$0,45$	$-0,04$	$0,57$	$0,06$
$err_{ToLOperator}$ (s)	$0,09$	$0,7$	$1,01$	$-2,4$	$0,85$	$-0,3$
err_{ID} (s)	$0,28$	$-0,2$	$-0,5$	$0,74$	$-0,39$	
$err_{Numberoflaps}$:	0					

Tabella 4.9: Second Trial Errors. In yellow are underlined cells with the max error value.

From tabs' analysis, we can observe that there's no error in number of strokes detection. The error in time of lap registers its maximum value in the first lap $(-1,15s)$ whereas in the other laps the error is small. The highest errors in computing the inversion duration are registered in the forth lap $(0,74s)$ while the other errors are smaller than $1s$. Every laps are detected so that there's no error in number of laps detection. The highest error in time of lap detection made by the operator is of $-2,4s$. The other values are very different between them.

Third Trial

The algorithm outputs of the third trial are shown in Tabella 4.10.

indexes/lap	lap1	lap2	lap3	lap4	lap5	lap6
Nos	16	16	15	15	16	14
ToL (s)	$18,52$	$20,92$	$20,16$	$20,96$	$21,08$	20
ID (s)	$5,2$	$5,12$	$6,04$	$6,52$	$5,68$	
Number of laps:	6					

Tabella 4.10: Algorithm Results: third trial.

The data obtained by the video analysis are reported in Tabella 4.11.
Time of laps data obtained by the operator are shown in Tabella 4.12

indexes/lap	lap1	lap2	lap3	lap4	lap5	lap6
Nos	14	16	15	15	16	14
ToL (s)	$19,8$	$20,82$	$20,13$	$20,83$	$20,72$	$19,25$
ID (s)	$4,9$	$5,82$	$5,86$	$5,53$ $6,52$		
Number of laps:	6					

Tabella 4.11: Video Results: third trial.

index/lap	lap1	lap2	lap3	lap4	lap5	lap6
ToL Operator (s)	22	19	20	21	21	20

Tabella 4.12: Time of Lap given by the operator.

The error found with the comparison between algorithm and video data are shown in Tabella 4.13.

indexes/lap	lap1	lap2	lap3	lap4	lap5	lap6
err_{Nos}	2	0	0	0	0	0
$err_{ToL}\,(s)$	$-1,28$	$0,1$	$0,03$	$0,13$	$0,36$	$0,75$
$err_{ID}\,(s)$	$0,3$	$-0,7$	$0,18$	$0,99$	$-0,84$	
$err_{ToLOperator}\,(s)$	$2,2$	$-1,82$	$-0,13$	$0,17$	$0,28$	$0,75$
$err_{Numberoflaps}$:	0					

Tabella 4.13: Third Trial Errors. In yellow are underlined cells with the max error value.

Through the observation of tabs, we can affirm how the maximum error in number of strokes detection is made in the first lap (2 strokes more than that seen in the relative video) as well as the maximum error in time of lap ($-1,28s$). Nevertheless the other laps, when talking about time of lap, show little errors. This can be said also regarding the number of strokes: the other laps has a null error. The maximum error detected in inversion duration is about $0,99s$ in the fourth lap. The other values are lower than one second. When considering the number of laps, we can see how all the laps are correctly detected: thus there is no mistake in lap number detection. The data given by the operator show a great error in the first lap 2,22 s. The other values have no tendency and the more of them are less than one second.

4.1.2 Second Session: Seven Infinity Gorgonzola

In this session we've tested different athletes for each trial.

Unfortunately the device gave us non calibrated data so we've decided to cut by ourselves the signals because the automatic detection made by the algorithm didn't work as well as for the previous trials. This prompted us to exclude the first and last errors in time of lap when assessing the maximum errors.

In these trials we chose not to fix the number of laps so that we would have been able to understand if the algorithm would have been responsive or not to the number of lap variations.

First Trial

In this trial was tested a male athlete which information can be seen in Tabella 4.14.

Name	A.
Surname	T.
Gender	Male
Age	42
Level	Master

Tabella 4.14: First Athlete: general features.

The algorithm outputs of the first athlete of the second session are shown in Tabella 4.15.

indexes/lap	lap1	lap2	lap3	lap4	lap5	lap6
Nos	20	20	19	20	21	21
ToL (s)	19.36	$23,12$	$23,4$	$24,36$	$24,36$	$25,4$
ID (s)	$4,28$	$6,08$	$5,04$	$5,48$	$4,76$	
Number of laps:	6					

Tabella 4.15: Algorithm Results: First athlete second session.

The data obtained by the video analysis are reported in Tabella 4.16.

Time of laps data obtained by the operator are shown in Tabella 4.17

The error found from the comparison between algorithm and video data are shown in Tabella 4.18.

Through a careful analysis of data, we can see that the maximum error in number of strokes is of one stroke: in particular in the first lap is registered one more stroke. The maximum error in time of lap detection is of $0,4s$ in the second lap. The other values are all less than one second comparing

indexes/lap	lap1	lap2	lap3	lap4	lap5	lap6
Nos	19	20	19	20	21	21
ToL (s)	$20,31$	23	23	$24,23$	$24,18$	$24,4$
ID (s)	$5,02$	$5,26$	$5,04$	$5,05$	$4,18$	
Number of laps:	6					

Tabella 4.16: Video Results: Second session first athlete.

index/lap	lap1	lap2	lap3	lap4	lap5	lap6
ToL Operator (s)	$20,04$	$23,76$	$23,43$	$24,48$	$24,41$	$24,43$

Tabella 4.17: Time of Lap given by the operator.

indexes/lap	lap1	lap2	lap3	lap4	lap5	lap6
err_{Nos}	1	0	0	0	0	0
err_{ToL} (s)	$-0,95$	$0,12$	$0,4$	$0,13$	$0,18$	1
$err_{ToLOperator}$ (s)	$0,27$	$-0,76$	$-0,43$	$-0,25$	$0,23$	$0,03$
err_{ID} (s)	$-0,74$	$0,82$	0	$0,43$	$0,58$	
$err_{Numberoflaps}$:	0					

Tabella 4.18: First Athlete Errors. In yellow are underlined cells with the max error value.

them to the video analysis values. Considering the inversion duration, the maximum error is registered for the second lap $(0,82s)$. The other values are positive except for the first lap in which we've an error of $-0,74s$ but all these values are under one second. All the laps are recognized so the error in number of laps detection is null. Operator's error reach its peak in the second lap $(0,76s)$, the other values are all under half of second.

Second Trial

In this trial was tested a female athlete which information can be seen in Tabella 4.19.

Name	G.
Surname	G.
Gender	Female
Age	25
Level	Master

Tabella 4.19: Second Athlete: general features.

The algorithm outputs of the second athlete are shown in Tabella 4.20.

indexes/lap	lap1	lap2	lap3	lap4	lap5	lap6
Nos	20	22	23	24	23	24
ToL (s)	$20,4$	$24,16$	$25,76$	$26,8$	$26,64$	$26,8$
ID (s)	$5,68$	$5,04$	$5,64$	$6,12$	$6,08$	
Number of laps:	6					

Tabella 4.20: Algorithm Results: Second athlete second session.

The data obtained by the video analysis are reported in Tabella 4.21.

indexes/lap	lap1	lap2	lap3	lap4	lap5	lap6
Nos	19	22	23	24	23	24
ToL (s)	$21,73$	$24,42$	$25,73$	$26,89$	$26,73$	$19,8$
ID (s)	$5,57$	$5,24$	$5,33$	$6,27$	$5,96$	
Number of laps:	6					

Tabella 4.21: Video Results: Second session second athlete.

Time of laps data obtained by the operator are shown in Tabella 4.22

index/lap	lap1	lap2	lap3	lap4	lap5	lap6
ToL Operator (s)	$21,66$	$24,21$	$25,83$	$26,77$	$26,98$	$26,28$

Tabella 4.22: Time of Lap given by the operator.

The error found with the comparison between algorithm and video data are shown in Tabella 4.23.

indexes/lap	lap1	lap2	lap3	lap4	lap5	lap6
err_{Nos}	1	0	0	0	0	0
$err_{ToL}\,(s)$	$-1,33$	$-0,26$	$0,03$	$-0,09$	$-0,09$	$-0,21$
$err_{ToLOperator}\,(s)$	$-0,07$	$-0,21$	$0,1$	$-0,12$	$0,25$	$-0,73$
$err_{ID}\,(s)$	$0,11$	$-0,2$	$0,31$	$-0,15$	$0,12$	
$err_{Numberoflaps}$:	0					

Tabella 4.23: Second Athlete errors. In yellow are underlined cells with the max error value.

Paying attention to the error table, we can conclude that the maximum error in number of stroke detected by the algorithm is of one stroke. In particular in lap1 the algorithm recognized one stroke more than that observed in the related video. Talking about the error in time of lap, we have an overestimation in time of the second lap ($-0,26s$). However all the values are less than one seconds. In the inversion duration we have the maximum error in correspondence of the third lap ($0,31s$). The other values are all little (less than one half of second). The number of laps coincides with the one observed in the relative video. The highest error achieved by the operator can be seen in the last lap ($-0,73s$). Observing the other values we can't found error bigger than five cents of second.

Third trial

The features of the male athlete tested in this trial can be seen in Tabella 4.24.

Name	A.
Surname	F.
Gender	Male
Age	30
Level	Master

Tabella 4.24: Third Athlete: general features.

The algorithm outputs of the third athlete of the second session are shown in Tabella 4.25.

indexes/lap	lap1	lap2	lap3	lap4	lap5	lap6	lap7	lap8	lap9	lap10
Nos	17	17	18	19	19	19	19	19	19	20
ToL (s)	21, 12	23, 24	23, 12	24, 6	24, 64	24, 48	24, 28	24, 88	24, 8	25, 96
ID (s)	5, 56	6, 76	4, 64	6, 96	6, 24	6, 12	6, 12	6, 64	5, 84	
Number of laps:	10									

Tabella 4.25: Algorithm Results:Third athlete second session.

The data obtained by the video analysis are reported in Tabella 4.26.

indexes/lap	lap1	lap2	lap3	lap4	lap5	lap6	lap7	lap8	lap9	lap10
Nos	16	18	18	19	19	19	19	19	19	20
ToL (s)	21, 76	23, 45	23, 3	24, 46	24, 36	24, 48	24, 36	25	25	25, 26
ID (s)	5, 5	5, 33	5, 36	6	5, 17	5, 33	5, 5	5, 69	5, 06	
Number of laps:	10									

Tabella 4.26: Video Results: Second session third athlete.

Time of laps data obtained by the operator are shown in Tabella 4.27

index/lap	lap1	lap2	lap3	lap4	lap5	lap6	lap7	lap8	lap9	lap10
ToL Operator (s)	21, 34	23, 7	23, 64	24, 82	24, 87	24, 94	24, 78	25, 28	25, 18	25, 4

Tabella 4.27: Time of Lap given by the operator.

The error found with the comparison between algorithm and video data are shown in Tabella4.28.

indexes/lap	lap1	lap2	lap3	lap4	lap5	lap6	lap7	lap8	lap9	lap10
err_{Nos}	1	−1	0	0	0	0	0	0	0	0
err_{ToL} (s)	−0, 6	−0, 21	−0, 18	0, 14	0, 28	0	−0, 08	−0, 12	−0, 2	0, 86
$err_{ToLOperator}$ (s)	−0, 42	0, 25	0, 34	0, 36	0, 51	0, 46	0, 42	0, 28	0, 18	0, 14
err_{ID} (s)	0, 06	1, 43	−0, 36	0, 96	1, 07	0, 79	0, 62	0, 95	0, 78	
$err_{Numberoflaps}$:	0									

Tabella 4.28: Third Athlete errors. In yellow are underlined cells with the max error value.

Looking at the tabs, we can see that the maximum error in number of strokes detection is of one stroke in the first (one more than that seen in video) and second lap (one less that that seen in video). The maximum error made by the algorithm in the determination of lap time is encountered in lap five $(0, 28s)$. The other values are different but all of them are under one second. When considering the inversion duration, the maximum error is made in lap2 $(1, 43)$. The other values are, six of them, less than one seconds and the others less than 2 seconds (around one second and an half). The number of laps is the same as that verified in the video analysis. The error in time of lap detection made by the operator is quasi-steady. Otherwise the maximum error can be seen in lap5 $(0, 51s)$.

Fourth trial

The features of the male athlete tested in this trial can be seen in Tabella4.29.

Name	A.
Surname	M.
Gender	Male
Age	24
Level	Master

Tabella 4.29: Fourth Athlete: general features.

The algorithm outputs of the fourth athlete are shown in Tabella 4.30. The data obtained by the video analysis are reported in Tabella4.31.

indexes/lap	lap1	lap2	lap3	lap4
Nos	16	17	17	18
ToL (s)	$20,2$	$23,08$	$22,56$	$24,4$
ID (s)	$6,32$	$5,76$	$5,84$	
Number of laps:	4			

Tabella 4.30: Algorithm Results:fourth athlete second session.

indexes/lap	lap1	lap2	lap3	lap4
Nos	16	17	17	18
ToL (s)	$21,5$	$23,13$	$22,31$	$22,5$
ID (s)	$5,83$	$6,27$	$5,6$	
Number of laps:	4			

Tabella 4.31: Video Results: Second session fourth athlete.

Time of laps data obtained by the operator are shown in Tabella4.32

index/lap	lap1	lap2	lap3	lap4
ToL Operator (s)	$20,83$	$23,11$	$22,72$	$22,97$

Tabella 4.32: Time of Lap given by the operator.

The error found with the comparison between algorithm and video data are shown in Tabella4.33.

indexes/lap	lap1	lap2	lap3	lap4
err_{Nos}	0	0	0	0
$err_{ToL}\,(s)$	$-1,3$	$-0,05$	$0,25$	$1,9$
$err_{ToLOperator}\,(s)$	$-0,67$	$-0,02$	$0,41$	$0,47$
$err_{ID}\,(s)$	$0,49$	$-0,51$	$0,24$	
$err_{Numberoflaps}$:	0			

Tabella 4.33: Fourth Athlete errors. In yellow are underlined cells with the max error value.

Paying attention to the tabs of this trial, we can see how there's no error in number of stroke detection. In time of lap recognition the maximum error achieved is about $0,25s$ and the other values (excluding the first and last lap) are smaller than one half of second. The maximum error in inversion time detection is of $-0,51s$ so that all the values are under one half of second. All the lap are recognized, thus the error in number of lap recognition is null. The operator error is quite small and reaches its maximum value in the first lap $(-0,67)$.

Fifth trial

In this lap, the athlete was a woman whose features are shown in Tabella4.34.

Name	E.
Surname	C.
Gender	Female
Age	22
Level	Master

Tabella 4.34: Fifth Athlete: general features.

The algorithm outputs of the fifth athlete are shown in Tabella4.35.

indexes/lap	lap1	lap2	lap3	lap4	lap5	lap6
Nos	21	22	21	22	22	24
ToL (s)	$21,08$	$22,84$	$22,36$	$23,68$	$22,88$	$25,16$
ID (s)	$5,28$	$4,24$	$5,92$	$4,6$	$4,88$	
Number of laps:	6					

Tabella 4.35: Algorithm Results:fifth athlete second session.

The data obtained by the video analysis are reported in Tabella4.36.

indexes/lap	lap1	lap2	lap3	lap4	lap5	lap6
Nos	20	22	21	22	22	23
ToL (s)	$21,33$	23	$22,77$	$23,79$	$22,89$	$23,89$
ID (s)	$5,2$	$4,66$	$5,27$	$4,79$	$4,73$	
Number of laps:	4					

Tabella 4.36: Video Results: Second session fifth athlete.

Time of laps data obtained by the operator are shown in Tabella4.37

index/lap	lap1	lap2	lap3	lap4	lap5	lap6
ToL Operator (s)	$20,59$	$23,01$	$22,72$	$23,76$	$22,94$	$23,7$

Tabella 4.37: Time of Lap given by the operator.

The error found with the comparison between algorithm and video data are shown in Tabella4.38.

indexes/lap	lap1	lap2	lap3	lap4	lap5	lap6
err_{Nos}	1	0	0	0	0	0
err_{ToL} (s)	$-0,25$	$0,16$	$-0,41$	$-0,11$	$-0,01$	$1,27$
$err_{ToLOperator}$ (s)	$-0,74$	$0,01$	$-0,05$	$-0,03$	$0,05$	$-0,19$
err_{ID} (s)	$0,08$	$-0,42$	$0,65$	$-0,19$	$0,15$	
$err_{Numberoflaps}$ (s):	0					

Tabella 4.38: Fifth Athlete second session errors. In yellow are underlined cells with the max error value.

Observing results of this lap, we can conclude that the highest error in number of stroke detection is made by the algorithm in the first lap (one stroke more than that shown in video). In time of lap , all values are less than one half of second and the error's peak is gained in the third lap ($-0,41s$). Concerning the error in inversion duration, the algorithm made the highest error in the third lap ($-0,65s$). All the lap are recognized, thus the error in number of lap recognition is null. Considering the error made by the operator, we can assess that the maximum error is about one second (more specifically $-0,74s$). The other values are all very little (under two cents of second).

Sixth trial

The male athlete physical features can be seen in Tabella4.39.

Name	A.
Surname	M.
Gender	Male
Age	23
Level	Master

Tabella 4.39: Sixth Athlete: general features.

The algorithm outputs of the sixth athlete are shown in Tabella4.40.

indexes/lap	lap1	lap2	lap3	lap4	lap5	lap6
Nos	18	20	19	21	22	23
ToL (s)	$21,96$	$24,36$	$23,6$	$25,08$	$22,32$	$23,16$
ID (s)	$5,92$	$5,4$	$4,32$	$3,64$	$4,52$	
Number of laps:	6					

Tabella 4.40: Algorithm Results:sixth athlete second session.

The data obtained by the video analysis are reported in Tabella4.41.

indexes/lap	lap1	lap2	lap3	lap4	lap5	lap6
Nos	19	20	20	21	22	23
ToL (s)	21, 69	24, 3	24	25, 56	22, 5	22, 3
ID (s)	5, 17	4, 87	3, 9	3, 47	3, 97	
Number of laps:	6					

Tabella 4.41: Video Results: Second session sixth athlete.

Time of laps data obtained by the operator are shown in Tabella4.42

index/lap	lap1	lap2	lap3	lap4	lap5	lap6
ToL Operator (s)	21, 39	24, 71	24, 1	25, 6	22, 8	22, 31

Tabella 4.42: Time of Lap given by the operator.

The error found with the comparison between algorithm and video data are shown in Tabella4.43.

indexes/lap	lap1	lap2	lap3	lap4	lap5	lap6
err_{Nos}	-1	0	yellow -1	0	0	0
err_{ToL} (s)	0, 27	0, 06	$-0, 4$	$-0, 48$	$-0, 18$	0, 86
$err_{ToLOperator}$ (s)	$-0, 3$	0, 41	0, 1	0, 04	0, 3	0, 01
err_{ID} (s)	0, 75	0, 53	0, 42	0, 17	0, 55	
$err_{Numberoflaps}$:	0					

Tabella 4.43: Sixth Athlete second session errors. In yellow are underlined cells with the max error value.

Looking at the tables, we can conclude that the algorithm loses one lap respectively in the first and third lap. In time of lap, the maximum error made by the algorithm is of $-0, 48s$ in the fourth lap. The other values are all under an half of second. Talking about inversion time, we have a peak in the error in the first lap $(0, 75s)$ and the other values, except for the fourth lap, are all around $0, 5s$. All the laps are recognized, so the error in number of lap detection is null. The highest value in time of lap error made by the operator is of $0, 41s$. Observing also the other value, they are different but all near zero.

Seventh trial

The information about the seventh athlete are reported in Tabella4.44.

The algorithm outputs of the seventh athlete are shown in Tabella4.45.

Name	M.
Surname	B.
Gender	Male
Age	30
Level	Master

Tabella 4.44: Seventh Athlete: general features.

indexes/lap	lap1	lap2	lap3	lap4	lap5	lap6	lap7	lap8
Nos	13	14	13	15	14	15	14	17
ToL(s)	18, 32	22, 16	21, 64	23, 88	22, 44	24, 12	23, 04	24, 32
ID(s)	5, 68	7	5, 92	5, 4	6, 68	5, 32	6, 4	
Number of laps:	8							

Tabella 4.45: Algorithm Results:seventh athlete second session.

The data obtained by the video analysis are reported in Tabella4.46.

indexes/lap	lap1	lap2	lap3	lap4	lap5	lap6	lap7	lap8
Nos	13	14	13	15	14	15	14	15
ToL(s)	19, 43	22, 53	21, 96	24, 36	23, 07	24, 69	23, 1	24, 2
ID (s)	5, 59	6, 3	5, 76	5, 5	5, 88	5, 27	6, 47	
Number of laps:	8							

Tabella 4.46: Video Results: Second session seventh athlete.

Time of laps data obtained by the operator are shown in Tabella4.47

index/lap	lap1	lap2	lap3	lap4	lap5	lap6	lap7	lap8
ToL Operator (s)	19, 02	23, 9	22, 1	24, 09	23, 09	24, 47	23, 8	24, 3

Tabella 4.47: Time of Lap given by the operator.

The error found with the comparison between algorithm and video data are shown in Tabella4.48.

Analyzing data, we can conclude that the greatest error in number of strokes due to the algorithm is in lap8 (two more strokes detected than that in video). The error in lap time is always less than one second and the maximum error can be seen in lap5 ($-0,63s$). Considering the inversion duration, we can affirm how the maximum error is in lap five (0,8 s) but however all the values are littler than one second. There's no mistake in number of laps detection. Viewing the errors made by the operator in time

indexes/lap	lap1	lap2	lap3	lap4	lap5	lap6	lap7	lap8
err_{Nos}	0	0	0	0	0	0	0	2
$err_{ToL}\,(s)$	$-1,11$	$-0,37$	$-0,32$	$-0,48$	$-0,63$	$-0,57$	$-0,06$	$0,12$
$err_{ToLOperator}\,(s)$	$-0,41$	$1,37$	$0,14$	$-0,27$	$0,02$	$-0,22$	$0,7$	$0,1$
$err_{ID}\,(s)$	$0,09$	$0,7$	$-0,16$	$-0,1$	$0,8$	$0,05$	$-0,07$	
$err_{Numberoflaps}$:	0							

Tabella 4.48: Seventh Athlete errors. In yellow are underlined cells with the max error value.

of lap detection, we can conclude that the greatest error is made in second lap ($-1,37s$). Nevertheless the other values are all under the second.

Eighth trial

The general features of the eighth athlete are shown in Tabella4.49.

Name	L.
Surname	C.
Gender	Male
Age	28
Level	Master

Tabella 4.49: Eighth Athlete: general features.

The algorithm outputs of the eight athlete are shown in Tabella4.50.

indexes/lap	lap1	lap2	lap3	lap4	lap5	lap6	lap7	lap8
Nos	16	19	19	19	19	21	21	21
ToL (s)	$19,4$	22	$21,72$	$22,56$	$21,44$	$22,2$	$21,52$	$23,08$
ID (s)	$5,96$	$4,16$	$4,12$	$4,68$	$4,64$	$4,2$	$4,2$	
Number of laps:	8							

Tabella 4.50: Algorithm Results: eighth athlete second session.

The data obtained by the video analysis are reported in Tabella4.51.

Time of laps data obtained by the operator are shown in Tabella4.52

The error found with the comparison between algorithm and video data are shown in Tabella4.53.

Looking at the previous tables, we can affirm how the only error made by the algorithm in number of strokes detection is of one stroke in lap4. Next, passing to the time of lap detection, the highest value of the error is $-0,69$ in

indexes/lap	lap1	lap2	lap3	lap4	lap5	lap6	lap7	lap8
Nos	16	19	19	20	19	21	21	21
ToL (s)	19, 04	22, 31	21, 89	23, 23	21, 66	22, 89	21, 86	21, 69
ID (s)	5, 43	4, 23	4, 63	3, 8	4, 6	4, 56	4, 3	
Number of laps:	8							

Tabella 4.51: Video Results: Second session eighth athlete.

index/lap	lap1	lap2	lap3	lap4	lap5	lap6	lap7	lap8
ToL Operator (s)	20, 48	22, 4	22, 29	22, 98	22, 05	22, 66	21, 79	22, 01

Tabella 4.52: Time of Lap given by the operator.

indexes/lap	lap1	lap2	lap3	lap4	lap5	lap6	lap7	lap8
err_{Nos}	0	0	0	1	0	0	0	0
$err_{ToL}\,(s)$	0, 36	−0, 31	−0, 17	−0, 67	−0, 22	−0, 69	−0, 34	1, 39
$err_{ToLOperator}\,(s)$	1, 44	0, 09	0, 4	−0, 25	0, 39	−0, 23	−0, 07	0, 32
$err_{ID}\,(s)$	0, 53	−0, 07	−0, 51	0, 88	0, 04	−0, 36	−0, 1	
$err_{Numberoflaps}$:	0							

Tabella 4.53: Eighth Athlete second session errors. In yellow are underlined cells with the max error value.

the sixth lap. The other values are all under one second. Finally, observing the error in computing the inversion duration , we can note the greatest value in lap4. All the lap are recognized so that the error in number of lap detection is null. Considering the error made by the operator, the highest mistake done is of $1,44s$. The other values are all between 0 and $0,4s$.

Ninth trial

The information about the ninth athlete can be seen in Tabella4.54.

Name	S.
Surname	C.
Gender	Male
Age	28
Level	Master

Tabella 4.54: Ninth Athlete: general features.

The algorithm outputs of the ninth athlete are shown in Tabella4.55.

indexes/lap	lap1	lap2	lap3	lap4	lap5	lap6
Nos	20	21	21	22	24	24
ToL (s)	$18,68$	$21,92$	$21,6$	22	$21,16$	$22,08$
ID (s)	$5,8$	$5,12$	$4,96$	$4,24$	$3,68$	
Number of laps:	6					

Tabella 4.55: Algorithm Results:ninth athlete second session.

The data obtained by the video analysis are reported in Tabella4.56.

indexes/lap	lap1	lap2	lap3	lap4	lap5	lap6
Nos	19	21	21	22	23	24
ToL (s)	$19,83$	$22,76$	$21,59$	$22,23$	$21,06$	$20,89$
ID (s)	$5,59$	$5,33$	$4,76$	$3,92$	$3,73$	
Number of laps:	6					

Tabella 4.56: Video Results: Second session ninth athlete.

Time of laps data obtained by the operator are shown in Tabella4.57

index/lap	lap1	lap2	lap3	lap4	lap5	lap6
ToL Operator (s)	$20,19$	$22,26$	$21,94$	$22,25$	$21,23$	$21,08$

Tabella 4.57: Time of Lap given by the operator.

The error found with the comparison between algorithm and video data are shown in Tabella4.58.

indexes/lap	lap1	lap2	lap3	lap4	lap5	lap6
err_{Nos}	1	0	0	0	yellow 1	0
$err_{ToL}\,(s)$	$-1,15$	$-0,84$	$0,01$	$-0,23$	$0,1$	$1,19$
$err_{ToLOperator}\,(s)$	$0,36$	$-0,5$	$0,35$	$0,02$	$0,17$	$0,19$
$err_{ID}\,(s)$	$0,21$	$-0,21$	$0,2$	$0,32$	$-0,05$	
$err_{Numberoflaps}$:	0					

Tabella 4.58: Ninth Athlete second session errors. In yellow are underlined cells with the max error value.

The error in number of lap detection is of one more stroke in lap1 and lap5. Looking at the time of lap, the greater value is $-0,84s$ in lap2. The other values are all under 3 cents of second. The error in inversion duration detection is always under one second: the maximum error is of $0,32s$in lap4.

There's no error in number of lap count. Observing the times reported by the operator, we can conclude that the highest value crosschecked is $0,5s$. Otherwise the other value are respectively two of them around $0,2s$ and the other two around $0,35s$.

Tenth trial

The features of the male athlete tested in this trials are shown in Tabella4.14.

The algorithm outputs of the tenth athlete are shown in Tabella4.59.

indexes/lap	lap1	lap2	lap3	lap4	lap5	lap6
Nos	20	21	21	21	21	21
ToL (s)	20,52	23,6	23,8	24,88	24,64	25,2
ID (s)	4,96	4,24	4,12	4,2	4,28	
Number of laps:	6					

Tabella 4.59: Algorithm Results:tenth athlete second session.

The data obtained by the video analysis are reported in Tabella4.60.

indexes/lap	lap1	lap2	lap3	lap4	lap5	lap6
Nos	19	21	20	21	21	21
ToL (s)	21,59	23,79	24,13	25,26	24,63	24,03
ID (s)	4,56	4,89	4,17	4,5	4,07	
Number of laps:	6					

Tabella 4.60: Video Results: Second session tenth athlete.

Time of laps data obtained by the operator are shown in Tabella4.61

index/lap	lap1	lap2	lap3	lap4	lap5	lap6
ToL Operator (s)	21,24	23,74	24,29	25,14	24,87	24,09

Tabella 4.61: Time of Lap given by the operator.

The error found with the comparison between algorithm and video data are shown in Tabella4.62.

The maximum error in number of strokes detection is made in the first lap (one more stroke than that seen in video). Observing data about time of lap errors, we can say that the errors are all little and the maximum error made by the algorithm is in lap4 $(-0,38)$. Talking about inversion duration, we can see how all the errors are under the second and the highest error is made in lap2 $(-0,65s)$. The error in number of lap recognition is

indexes/lap	lap1	lap2	lap3	lap4	lap5	lap6
err_{Nos}	1	0	0	0	0	0
$err_{ToL}\ (s)$	$-1,07$	$-0,19$	$-0,33$	$-0,38$	$0,01$	$1,17$
$err_{ToLOperator}\ (s)$	$-0,35$	$-0,05$	$0,16$	$-0,12$	$0,24$	$0,06$
$err_{ID}\ (s)$	$0,4$	$-0,65$	$-0,05$	$-0,3$	$0,21$	
$err_{Numberoflaps}$:	0					

Tabella 4.62: Tenth Athlete errors. In yellow are underlined cells with the max error value.

null. Looking at tabs, it is also possible to see how the greatest error made by the operator is checked in the first lap ($-0.35s$). The other value are very little and don't go beyond $0,24s$.

4.2 Stroke Sensitivity

Using the GUI designed on purpose, we've verified if the strokes extracted by the algorithm were real strokes or other movement.

This observation let us computing a sort of sensitivity of the algorithm to the stroke recognition.

It was possible to compute this index only for the trials done in Lecco because it wasn't possible to synchronize the other trials. In Tabella4.63 are shown the results.

	First Trial	**Second Trial**	**Third Trial**
TP	93	91	91
FN	3	3	6
Sensitivity (%)	$96,875$	$96,809$	$93,814$
Mean Sensitivity (%)	95,833		

Tabella 4.63: Stroke Sensitivity results.

The last lap is that with the higher number of false negative while the other two laps shows the same number of false negative. Furthermore in the first lap we can see 93 true positive and in the other two trials we have two less true positive than the first one. The minimum sensitivity is registered in the last lap while, in the other two laps, the values are very closed. The mean sensitivity is near 96 %.

4.3 Discussion

4.3.1 Lap detection

In the number of lap recognition the algorithm seems to have no problems. In each session it has been recognized the right number of laps so we have a null error in number of lap recognition.

4.3.2 ToL Detection

In Figura4.1 it is shown the mean errors made in ToL detection.

We can see how the highest errors made by the algorithm are in two of

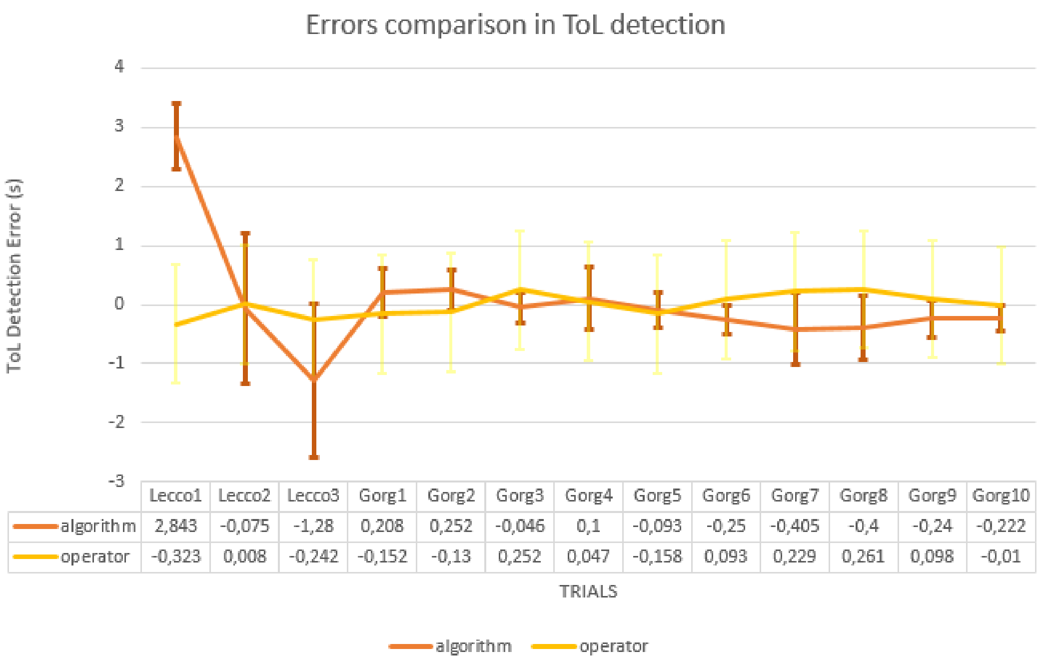


Figura 4.1: ToL detection: Algorithm (orange) and Operator (yellow) Errors comparison

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the Lecco trials. The first peak (of about 3 seconds), if compared with the results shown in Tabella4.5, is due to an imperfect algorithm useful signal detection (Figura4.2). This can be explained with a careful video analysis: in this trial the athlete, at the end of the trial, doesn't assume an upright position and she goes on swimming in frog style. This is recognizes by the algorithm as a part of the lap so that time of lap and number of strokes increase.

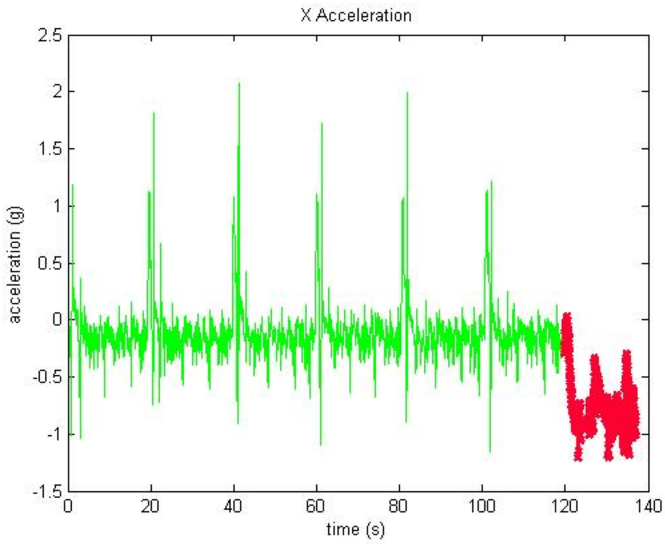

Figura 4.2: First trial in Lecco (X acceleration): error in useful signal detection.

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It is obvious that the red part would have not be considered because the athlete would have start to assume a vertical position.

We can also observe a similar phenomenon in the third trial (Figura4.3).

In red we can observe a clear peak that is due to the last of the three jumps made by the athlete for the synchronization and that is not part of the useful signal. This have introduced an error that is quite high (1,28 s) that affected the mean ToL error $(1,28 \pm 0,67s)$.

The other trials show small mean errors (all the values are around zero). This ascertainment bring us to consider a possible improvement in useful signal detection since the algorithm, when not considering the extraction of the useful signals as in Gorgonzola trials, works well.

Comparing the mean errors made by the algorithm and the operator, they are almost the same excluding the previous mentioned trials in which the error is due to the algorithm ability in useful signal extraction. However the mean error in all trials is about $-0,002 \pm 0,53s$ against $0,030 \pm 0,81s$ of the algorithm. This difference becomes lower taking into account only the trials made in Gorgonzola: we have respectively for the algorithm $-0,1096\pm,2581s$ and for the operator $0,053 \pm 0,375s$.

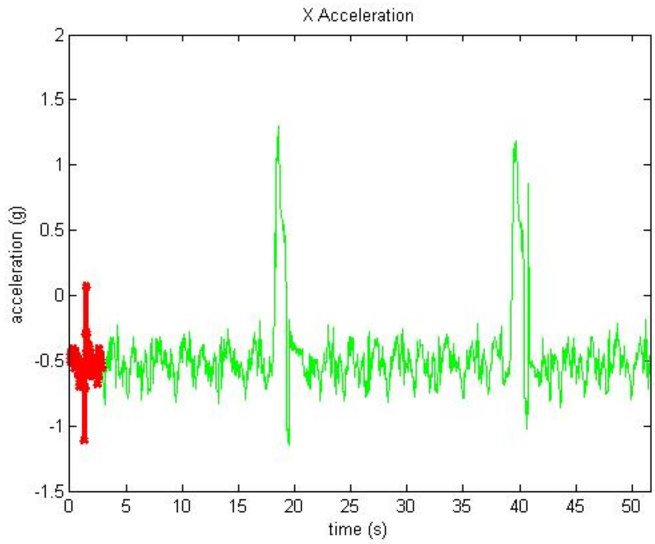

Figura 4.3: Third trial in Lecco (X acceleration): error in useful signal detection. In red it is underlined the no useful signals' part.

4.3.3 NoS Detection

In Figura4.4 it is shown the mean percentage error in NoS detection in each trial.

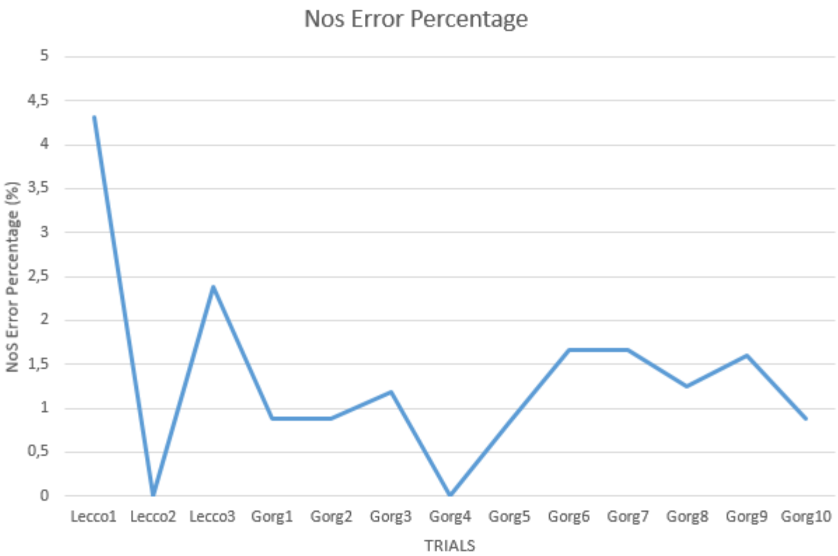

Figura 4.4: Average NoS percentage error in all trials.

As we can note from an accurate observation of the graph, the highest mean percentage error is obtained for the first trial in Lecco. In the same way as the error in recognition of the useful signal has affected the tol values, it has also affected the NoS recognition. Indeed, only in the last lap of this trial, we have an error of three strokes, that is the highest error in all trials. Furthermore in this trial we have another error of one lap in the first lap so the total number of strokes error is of 4 strokes. The only other trial in which the algorithm detect more than one stroke in a single lap, is the third trial.

On the other hand, in a large number of laps of different trials, we have a null error in number of strokes detection and the error doesn't go beyond one stroke.

Seldom it was difficult to establish a rule to exclude, or not, peaks in strokes count. It was necessary to introduce a sort of "refractoriness" period, but, rarely, the athlete do a stroke in proximity of the inversion. At the same time, some athletes execute some strange movements to prepare themselves to the turn, and, without any refractory period, them were recognize as strokes. This brings us to take a decision of "*cost and benefit* and this choice reduces the errors but can't totally eliminate it.

Furthermore some peaks are lost because are integrated in the higher peaks due to the rotation made by the athletes during turns. Maybe, analyzing turns with other sensors, as magnetometers or gyros, we can improve the strokes detection mechanism and reach higher level of sensitivity.

However the stroke sensitivity is good. The mean sensitivity is $95,83\%$, thus near 96%. The third lap in Lecco shows a strong reduction in true positive in favor of false negative. This let us say that, even if the value is not so low, there is an ample room for improvements.

4.3.4 ID detection

In Figura4.5 we can see the average algorithm errors in ID detection.

We can note as the highest value is reached in the third trial in Gorgonzola in which the most of the values are around one second with a peak of $1,43s$. The other values are all under the $0,5s$.

Nevertheless, we don't have to forgive that these are only mean values. We can say how the inversion detection is a sort of "*Achilles' heel*". An error higher than one second when the movement is executed on an average of 4/5 seconds are not acceptable.

We've advanced different hypothesis on the cause of these errors. At first we can obviously say that the errors in NoS detection inevitably affects the errors in ID detection when the errors are in the last stroke before the turn. As we have pointed out, in some laps some strokes peaks have merged with the peaks due to the natural rotation in turn. By the way the error in ID detection would be higher of, at least, one half of second because, a stroke,

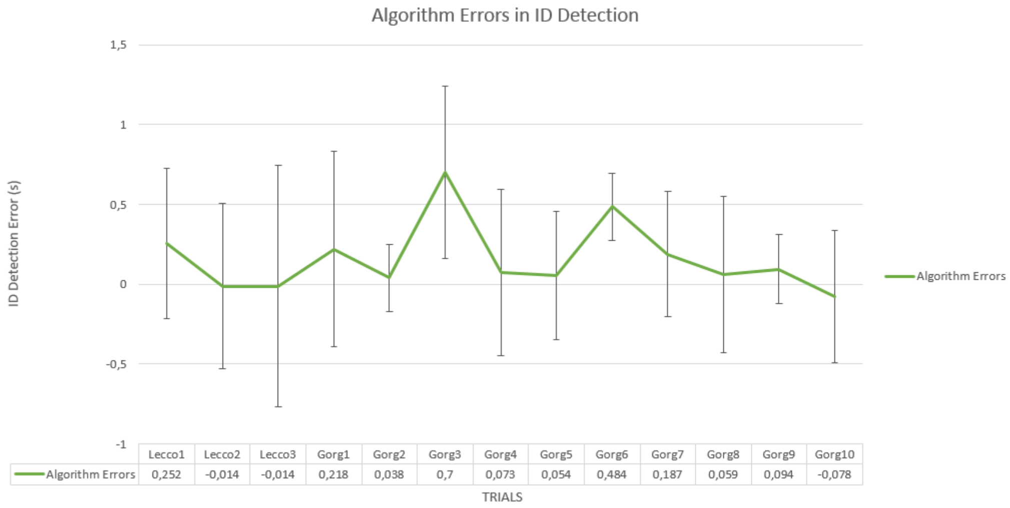

Figura 4.5: ID detection: algorithm average errors lap by lap.

has this average duration. Another, and maybe more plausible, cause can be found in the data filtering. As a matter of fact, when filtering with a FIR filter we introduce a delay. In this particular context, the moving average filters used was of 15 samples. Given that the delay of a FIR filter is of $(N-1)/2$ samples, in this case we have a delay of about $0,3s$. This can explain also the variability of this error: piling up several delays, sometimes the samples are anticipated reducing, or even furnishing a smaller value, than that seen in the video. Sometimes samples are delayed so that the errors become higher and higher.

This problems can be solved improving the NoS detection and, maybe, subtracting the delay given by the filtering stage on samples. Another way to solve all the problems linked to ID detection, is to introduce other sensors, as magnetometers and gyros, and detect, in a more severe way, the turn.

Capitolo 5

Conclusion and Future Developments

5.1 Trainers' Opinion

In order to have a feedback on our work, we decided to create a questionnaire in which trainers can express their opinion.

We have had the answers of six trainers of age comprises between 23 and 45 years. They all have an experience of, at least, two years while the person who has the highest experience has been working in this field for twenty five years. Their ages and experiences are shown in Tabella5.1

Name	**Surname**	**Age**	**Experience**
G.	B.	23	2
L.	R.	45	25
S.	F.	30	12
M.	B.	30	5
A.	C.	25	4
S.	N.	25	4

Tabella 5.1: Interviewees Information.

At first we asked them if they think that the wearable technology is of the utmost relevance for the objective evaluation of the preparation of an athlete and they all give us a positive answer. This is an important result even though we have only 6 interviewees: it means that trainers need such technology to go beyond the visual limitations in the evaluation of a complex athletic gesture as that made in swim.

We asked them also which are the most difficult information about swimmers performances that a trainer can obtain during a training session only using a qualitative observation. In this section we have many different answers that don't appear have a common line. What is very interesting is that all, in some way, refer to efficiency and heart rate, that, from a physiological point of view, are linked. Someone tells us that is also hard to have an idea of the body orientation of the swimmer and also of the lower limbs. This suggests us that the way in which the project is though, in respect to body orientation, efficiency and heart rate, can accomplish the trainers requests. Considering lower limbs, it is an interesting point to analyze but it seems, nowadays, a very difficult problem to solve.

Next we have ask them to evaluate, with a score from 1 (not at all) to 3 (a lot), the importance, in swimmers evaluation, of each index we have computed with the algorithm. Results are shown in Figura5.1.

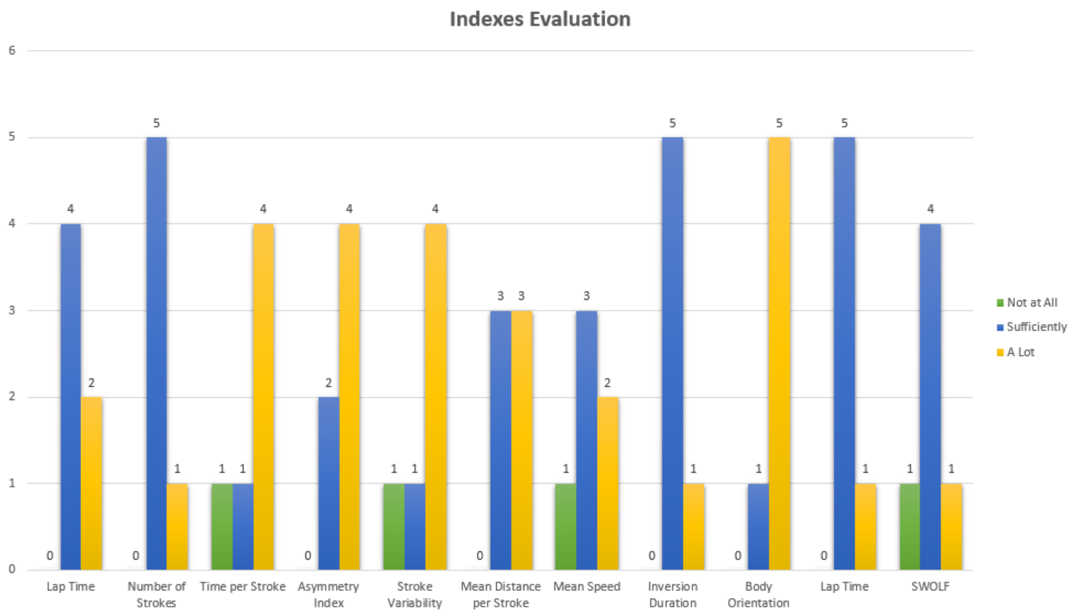

Figura 5.1: Trainers Indexes Evaluation.

From the figure shown above, we can observe how any index is considered useless: the maximum frequency obtained by the lowest score is of one. Body Orientation is the index that is considered by 5 of the 6 trainers very useful but also Time per Stroke, Asymmetry Index and Stroke Variability received four times the highest evaluation. Generally we can say that our indexes are appreciated by trainers and considered very important for the athletes evaluation.

Later we asked also which are the strong points and the weakness of the technologies nowadays on market. They tell us that most of these devices are not able to track, with high precision, the number of laps and to give a feedback on heart rate. In this sense our project respond to all of this request and, so, it seems to be an ideal alternative to what is present on market yet and to offer what the trainers want. The other topic underlined by interviewees is the importance of "*wearability*". Some previous studies on this issue made by the team of Sensibilab, bring us to consider that this research has a good solution. The higher location on the trunk of the device, let the athlete be free from any impediment. We also have a feedback from swimmers underwent to the previous trials, that tell us they were not able to distinguish if the device was insert in the pocket or not, giving them the sensation of not wearing any device. We also have indirectly understand that, one of the things that the public wants, is to see and be aware of what they can't see. This is the direction that, such devices, has to follow.

When asking them in what they think this device is lacking, they tell us that we can examine in depth the opportunity of give all these information in real time. This is a huge problem when talking about sports in a damp environment because water and transmissions are not compatible. It is also interesting what have been written by one of the trainers: he point out the necessity of one trainer to follow different athletes in the same training session. Another theme on what it is useful to linger, and that trainers pointed out, is the importance to have a feedback in terms of energy and power consumptions. This would be possible only with the integration of biological signals as the ECG. This is one of the crucial point of this project on which surely will be necessary to work.

At the end of the questionnaire we asked also if they would have suggest this kind of device to their athletes: five of them give an affirmative answer. This let us assuming that the public is ready to accept this useful instrumentation and to use it to improve their ability in swim evaluation.

5.2 Project Future Perspective and Comment

This work of thesis wants to be the starting point of a more complex and bigger project. The results obtained in this year are promising and, with some more efforts, the device can be realized in the near future.

Surely, as attests the spread of the wearable sports devices, we suppose that a similar device can be appreciated by the public.

Surely the ID identification has to be improved and more studies on the integration of different technologies, could help to solve this problem. The hardware provides an on board IMU that offers a three axial gyro and a magnetometer, so it is already to undergo to different studies on the possibility to use these data with the aim to improve the device.

With the use of the gyros, we can also improve the body orientation detection (pitch and roll angles) obtaining a better estimation. As a matter of fact, in literature [37], it was advised against to use only the accelerometer data even though the method give a good approximation of the angles. In the previous cited patent, it is also suggested a more reliable method for compute angles with gyros data.

Furthermore we have to understand if the useful signal detection can be improved by a specific automatic calibration algorithm or if it necessary to change the way in which it detects the start and the end of the training session. A possibility can be to provide, from the hardware point of view, a button that the athlete can press to assess that he is going to start or end his training session. Maybe, this button, can be positioned in the anterior part of the swimsuit so that it is easy to be pressed.

Surely the algorithm has also to be adapted to the evaluation of the other techniques (butterfly, backstroke and breaststroke) on the basis of the features and indexes extracted by these algorithm that seem to have a good feedback by trainers. This can be made using the same signal processing stages but adapting them to the specific features of the specific signal. This, obviously, necessitates the implementation of a technique identification block that, on the basis of the sportive gesture and signals features, can detect the specific style. For example, in backstroke, it is possible to create a specific code in which the signs of Z axis data can inform us on the horizontal position of the athletes body with face pointed up or down.

The theme of the real time feedback is the most interesting but, at the same time, the most difficult to be realized. Talking with my tutor, we think that, maybe, the use of Bluetooth 4 technology can be a good solution. This would let us to register data when the device is submerged in water and, then, once the athlete exits from water, data registered can be sent to an external device and can be visualized with the help of a specific software reducing data loss and going beyond the problem of communication in aquatic environment. This is only an hypothesis: specific test for the assessment of the real functioning of this technology on our purpose has to be done yet. Maybe, with this communication protocol, it would be possible to send data of different subjects to the trainers' device accomplishing the suggestion received with the questionnaire.

It would be also interesting to better understand and analyze the turn mechanism. We have just achieved some video that shows only the turn of different styles. In this way, in addition to the improvement in ID identification, we can study also the way to inform the trainer on how the movement is done. For example, the turn can be divided in three stages:

1. approach to the wall;
2. turn and push;
3. leaving from wall.

All of these stages, later, can be separately analyzed and processed.

Next, it is of the utmost importance, give, as feedback, the heart rate and some indexes about energy expenditure and calories burned. The sensors and system are ready to give information about the heart rate through the registration of the ECG signal. To overcome the approximate and erratic approach of on market device in energy consumption calculation , can be studied a methodology with which relates the ECG and heart rate information with the energy consumption. Maybe would be interesting search also a method to inform and be aware the trainer about swimmers' fatigue state.

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