International Doctoral Thesis/ Tesis Doctoral Internacional

Universidad de Granada

Influence of the new starting block with back plate on the kinematic variables of the swimming start

Análisis del efecto en la cinemática de la salida de natación
de los cambios recientes en el diseño de poyetes de salida

Programa de doctorado de biomedicina

Departamento de educación física y deportiva

Facultad de ciencias del deporte, Universidad de Granada

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Junio de 2016

Editor: Universidad de Granada. Tesis Doctorales
Autora: Sonia Taladriz Blanco
ISBN: 978-84-9163-073-9
URI: http://hdl.handle.net/10481/44594

DEPARTAMENTO DE EDUCACIÓN FÍSICA Y DEPORTIVA
FACULTAD DE CIENCIAS DEL DEPORTE
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Programa de Doctorado de Biomedicina

Sonia Taladriz Blanco

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En Granada, a 24 de Junio de 2016

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A Patricia, a Raúl B., a Flora y a mis padres

"Algún día todo tendrá sentido. Así que por ahora, ríete ante la confusión, sonríe a través de las lágrimas y síguete recordando que todo pasa por una razón"

THESIS SCOPE

INTRODUCTION

CHAPTER 1

Biomechanical advantages of the kick-start technique during the aerial phase

CHAPTER 2

Development of angular momentum about the mediolateral body axis during the kick-start technique

THESIS SCOPE

The swim start is the first component of a swimming race and although it is the shortest and the fastest phase, an effective start performance is essential for the success of a race, particularly in short events. The swim start allows swimmers to enter into the water faster than average swimming speed.

Historically swimmers have performed several start techniques in competitions, whereas today the kick-start is the most popular technique due to its great advantages. This start technique is characterized by an asymmetrical position of the swimmer´s feet on the starting block where the front foot is placed on the front edge and the rear foot is placed on a stable and adjustable surface on the rear edge of the block. This surface also referred to as back plate provides higher stability and the advantage is that the swimmer is able to develop larger force levels on the block than with older techniques (grab start or track start).

Among all variables included in the biomechanical analysis of the swimming starts, the angular momentum is a relevant variable due to its influence on the body position at the water entry and subsequently on the water phase performance. However, only a few studies focussed on the comparison of the different start techniques including the analysis of angular momentum data. Those studies comparing different starting techniques only analyse the amount of angular momentum produced at take-off and no study evaluates the development of the angular momentum during the block phase; flight phase and/or glide phase in a swimming start.

The main objective of this thesis is to study the kick-start performance by analysing the development of angular momentum. Additionally, this study highlights the advantages in terms of angular momentum and body rotation swimmers provide to the kick-start.

After a general introduction about the history, evolution and relevance of swim starts, and a brief description of the theoretical background about angular momentum, the thesis is divided into two chapters. Chapter 1 determines the most relevant factors for the improvement of the kick-start and Chapter 2 focuses on the analysis of the development of angular momentum about the mediolateral body axis from the starting signal until the gliding phase in the kick-start technique.

Each chapter is divided into two sections. Section 1.I (Chapter 1) focuses on the analysis of the advantages that kick-start technique provides on the block and during the flight phase in comparison with a grab start. It delineates the main advantage a kick-start allows swimmers to develop larger forces on the block within shorter time periods. This section also includes an evaluation of the relationship among the variables involved, on the block and in the air, and as a result it suggests some ways to improve the kick-start. We concluded that larger flight times and lower rear leg displacements on the block cause higher rotation of the body, which reduces the horizontal velocity in the water and makes a better kick-start performance. Section 1.II (Chapter 1) compares the mechanics of rotation on the block and during the flight phase for a kick-start and grab start. The study reveals that for the kick-start the main body rotation is produced by an upward displacement of the front leg towards to the rear leg during the flight phase. In contrast, the body rotation in the grab-start is produced by a displacement of the trunk. Although both strategies provide a similar entry into the water, the advantages which the kick-start has on the block makes it the better start for swimmers.

Angular momentum is one of the most important variables to analyse for the improvement of swimming starts. The angular momentum developed on the block determines the extent of body rotation performed during the flight phase. It is known that larger angular momentum at take-off allows for shorter times up to 5 m because of the larger body rotation acquired during the flight phase. In the Section 2.I (Chapter 2) we identified that higher front knee angle at starting position, with values between 135º-145º, and smaller shoulder angles increase the angular momentum developed on the block and hence produces a better kick-start.

Besides the larger angular momentum, larger flight times are required to produce larger body rotations during the flight. An increase in the body rotation during the flight phase in turn leads to a longer reduction in angular momentum after the feet immersion. Section 2.II describes that these results are associated with a powerful dolphin-kick after the feet immersion and a decrease in horizontal velocity at water entry.

At the end of each chapter a detailed conclusion section was included about the main results extracted of each study. Besides, the main results of this thesis are highlighted in a general conclusions section at the end of the thesis. An appendix with the definitions of the variables used in the analysis of the swimming starts, and a section describing the main limitations of our studies, the recommendations for future studies and practical applications are included at the end of this dissertation. A synopsis, in Spanish, is also included at the end of this thesis as required by the regulation of the University of Granada.

INTRODUCTION

THE SWIMMING STARTS

"The starts in swimming are an important time saver" (Lyttle & Blanksby, 2011). "Effective diving techniques enable swimmers to exploit the speed generated during the dive and to enter into the water faster than average swimming speed" (Vantorre, Chollet , & Seifert, 2014).

1. Historical background and relevance of the swimming start on the overall races performance

The swimming start is the first component of a swimming race followed by stroking, turning and finishing (Hay, Guimaraes, & Grimston, 1983). Its performance is quantitatively measured by the elapsed time between the start signal and the moment when the swimmer's head crosses an imaginary line set at 10 m (Arellano, Brown, Cappaert, & Nelson, 1994) or 15 m (Cossor & Mason, 2001; Issurin & Verbitsky, 2002) from the edge of the swimming pool.

The time invested in a start measured in 15 m represents approximately the 0.8-21.6% of the total time spent in the swimming races decreasing the percentage as much longer is the event distance (Mason & Cossor, 2000). During the last World Swimming Championships held in Barcelona (2013), in 50 m events, the time invested in the start represented a 24.08 ± 1.10% and a 24.84 ± 0.69% of the total time for males and females, respectively. In 100 m, this percentage decreases to 11.25 ± 0.59% for males and 11.78 ± 0.55% for females and in 800 m events the start time contributed to the overall race performance for 1.41 ± 0.03% and 1.43 ± 0.01% in males and females, respectively (Argüelles-Cienfuegos & De La Fuente-Caynzos, 2014). Despite the relatively small contribution over the total race, an effective start performance is an essential part of the swimming race, particularly in short events.

The swimming start is the shortest and the fastest phase of a swimming race. The swimmers invest around 8.0 s in its performance and they are able to achieve the highest average velocity of a race (Kennedy, Brown, Chengalur, & Nelson, 1990; Mason et al., 2000; Nelson, Arellano, Brown, & Cappaert, 1992). An improvement in the start can, on average, reduces the race time by a minimum of 0.10 s (Maglischo, 2003). In this regard and taking into account that the differences on the total swimming race performance are often determined by 0.01 s, an effective start could mean the success or the failure of the race. With the main objective to determine the relevant phases that contribute to the overall race performance were analysing the swimming performance in the 1992 Olympic Games, 1998 World Swimming Championship, 1999 Pan Pacific Swimming Championship and in Sydney 2000 Olympic Games. Results showed large positive correlations (r = 0.50 - 0.87) between the start time and the final race time for both short (50- 100 m) and longer (800- 1500 m) distances (Arellano et al., 1994; Arellano et al., 2001; Mason & Cossor, 2000; Mason et al., 1998; Thompson, Haljand, & MacLaren, 2006).

The relevance of the swimming start on the total race performance have led to the development of different start techniques and to several biomechanical studies with the objective to find the most efficient start technique. The first experimental study including an analysis of the swimming start was conducted in 1966 (Gentile, 1966). In this study, the start technique used was the nowadays-called *conventional start* (Figure 1). In this technique, the swimmers' feet were placed over the forward edge of the block, with a similar distance to the shoulder width. The knees and the hip were slightly flexed and the head, neck and trunk were placed nearly horizontal to the plane of the water surface. In this start, the upper limbs could be placed in two different positions: 1) extended back in line with the upper trunk which leads to place the hands above the hips (figure 1a) and 2) hang the hands approximately thirty centimetres in front of the block (figure 1b) (Bloom, 1978; Lewis, 1980). After the starting signal, the first upper arms position (extended back, figure 1a) enabled a swing of the arms downwards and forward to an overhead-extended position. The second upper limbs position (hang the hands in front of the block, figure 1b) allows to swimmers perform two displacements of the arms after the starting signal. A swing backwards, in a clockwise direction, above the hip level and then forward to an overhead position; or, a circular arms swing where the swimmers firstly performed an upward and backward arms displacement and then a downward and forward displacement to an overhead position.

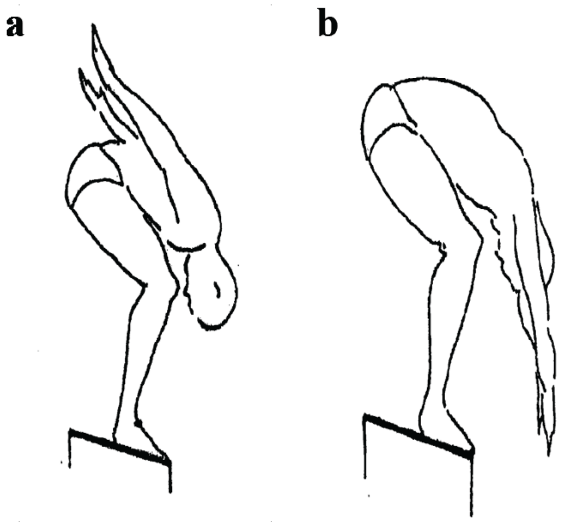

Figure 1. Different arms position for the conventional start technique, arms position extended back (a) and hang down position (b) (Lewis, 1980).

In 1967, Eric Hanauer introduced a new start technique, the *grab start*. However this technique was not popular until the Olympic Games in Munich 1972. The grab start has a similar lower limbs position on the block to the conventional start. The main difference between these techniques was the upper limbs position on the block. In the grab start, the swimmers' feet were placed parallels each other on the front edge of the block and with a similar distance to the shoulder width. However, the knees and hips were flexed to allow the hands to grip the front edge of the starting block. After the starting signal the arms swing out in front of the body (Figure 2a) (Lewis, 1980).

After the introduction of the grab start technique many studies were made in order to determine the advantages and disadvantages of this technique compared with the conventional start. The time spent between the starting signal until the first observable movement of the swimmer (reaction time), the elapsed time from the first observable movement until the moment when the feet left the block (movement time) and the total time on the block (time spend on the block from the starting signal until the moment when the feet left the block) was shown shorter for the grab start than for the conventional start (Ayalon, Van Gheluwe, & Kanitz, 1975; Bloom, 1978; Bowers & Cavanagh, 1975; Lewis, 1980; Roffer, 1972). In spite of the shorter time spent on the block, the swimmers obtained similar take-off velocity than in the conventional start. In grab start, the swimmers were able to develop larger force levels in shorter times, because using this start the swimmers can use both, the legs and the arms, to push off the block and to adopt a more tensed position to generate a force with the most powerful muscle groups of the trunk and arms (Bloom, 1978). In contrast, performing a conventional start, the movement of the arms after the starting signal produced an increase in the time invested on the block (Bowers & Cavanagh, 1975; Disch, Hosler, & Bloom, 1979; Lewis, 1980). These latter temporal disadvantages caused by the arms swing produced on the block in the conventional start, and the advantages described above of the grab start, resulted in the decline of the conventional start in individual swimming races.

Until 2009, the grab start was used for swimmers in international competitions. As consequence of the thirty-seven years of popularity of this technique, a couple of variations appeared on the original technique; the *tuck start* (Figure 2b) and the *one-handed grab start* (Figure 2c). The differences between these variations lie in the position of the upper limbs in the starting block. The tuck start was characterized by a lateral grip of the hands to both sides of the starting block and a very grouped body position. This position gave greater stability to the swimmer due to the absence of an upper limb movement and a body position with the centre of mass very close to the edge of the starting block, which reduced the time invested on the block.

In the one-handed grab start, one of the hands gripped the front edge of the starting block in order to increase the stability at starting position and allow the swimmer to push off the block with the hands after the starting signal. The other hand was elevated and extended behind the swimmer to produce an additional impulse by a swing of the arm from backward to forward after the signal (Brik, & Woods, 1976; Lewis, 1980; Woelber, 1983). However, both variations were not well accepted by swimmers and they never became popular.

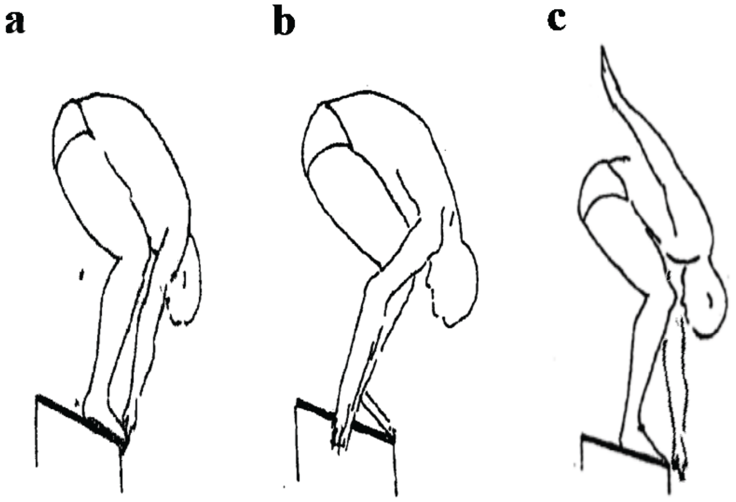

Figure 2. Variations of the grab start technique. Grab start (a), tuck start (b) and one-handed grab start (c) (Lewis, 1980).

In 1973, Fitzgerald introduced a new start technique, the *track start* (Fitzgerald, 1973). This technique was characterized by an asymmetrical feet position on the block. One foot was placed on the front edge and the other on the rear part of the starting block (Figure 3). Similar to the last techniques, in the track start the knees and hips were flexed to allow the hands grip the front edge with a similar distance to the shoulder width position each other. After the starting signal the arms were swung out in front of the body while the rear foot firstly and then the front foot pulled the block to move the body in a forward direction.

In spite of the visible differences with the grab start and the increasing of the stability that the asymmetrical feet position provides to swimmers on the block, both techniques, grab start and track start, coexisted for more than forty years due to disagreements on their advantages and disadvantages. Several authors did not give priority to the use of one technique over the other, concluding that the best start was the one most practiced by the swimmer (Blanksby, Nicholson, & Elliot, 2002; Jorgić et al., 2010; Mason, Alcock, & Fowlie, 2007; Thanopoulos et al., 2012; Vantorre, Seifert, Fernandes, Vilas-Boas, & Chollet, 2010a). Other investigations gave preference to the track start over the grab start (Holthe & McLean, 2001; Issurin & Verbitsky, 2002) or the opposite (Ayalon et al., 1975; Counsilman, Counsilman, Nomura, & Endo, 1986; Krüger, Wick, Hohmann, El-Bahrawi, & Koth, 2003; Zatsiorsky, Bulgakova, & Chaplinsky, 1979).

Figure 3. Track start technique.

In 1985, LaRue (1985) developed a variation of the track start technique, the *bunch start* (Figure 4). In this technique, the starting block was modified to add a vertical support for the rear foot similar to the block in running. Consequently, the swimmers were able to push backward with the rear leg and push longer backward with the front leg. This modification of the track start was unsuccessful because the design of the starting block did not increase significantly the horizontal impulse. Moreover, further risk of rear foot slip on the surface of the block resulted in a critical loss in the applied horizontal force (LaRue, 1985).

Recently, in 2009 a new starting block that features an “adjustable and slanted footrest” (FR.2.7. Starting platforms in FINA’s rules) was approved by International Swimming Federation (FINA) which solves the problems associated to the vertical support of the bunch start. This starting block represented a dramatic improvement in the swimming starts offering to the swimmers the advantage to place their rear foot on a stable and adjustable surface depending of their preferences. This new start technique was called *kick-start*.

Currently, the kick-start has been adopted by the most of the swimmers in international competitions because of the larger advantages that this start provides to the swimmers in relation to the grab start and track start. All the studies evaluating the kick-start showed important advantages regarding the take-off velocity, block time, flight time and time to 5 m, 7.5 m, 10 m and 15 m compared with the grab start and track start technique (Beretić, Durović, & Okičić, 2012; de Leva, 1996; Honda, Sinclair, Mason, & Pease, 2012; Nomura, Takeda, & Takagi, 2010; Ozeki, Sakurai, Taguchi, & Takise, 2012).

The study of the kick-start technique and its advantages and differences in relation to the grab start and track start are the object of the present thesis.

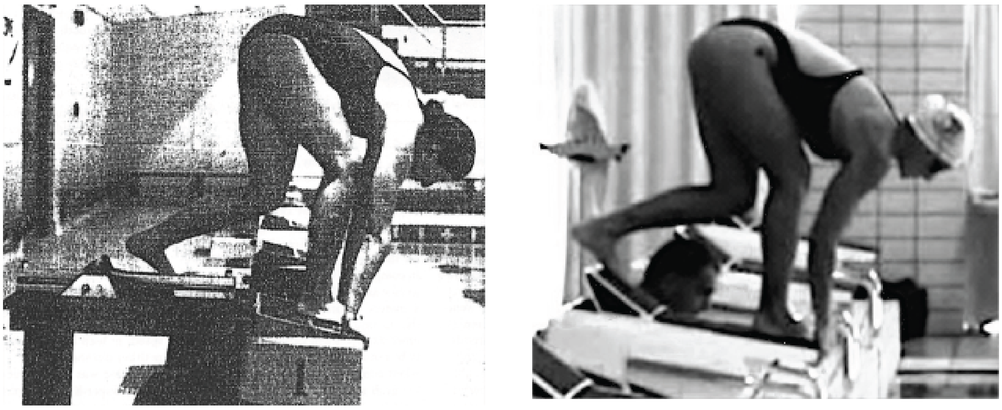

Figure 4. Bunch start (LaRue, 1985) and kick-start technique.

2. Last evolution of the swimming starts

Throughout history, the start technique has experienced numerous changes. A wide number of biomechanical studies were made to define the characteristics and analyse the advantages, disadvantages, and differences among the types of swimming starts. The start technique performed by swimmers in competition has been changing over the past of the years but the grab start and track start have remained in used for more than forty years. Until 2009, none start technique had shown larger advantages than the grab start and track start.

In late 2009, FINA has approved the use of a new starting block, the Omega OSB11. This block is similar to the conventional starting block, however the new block is provided with a mobile back plate that could be set in five different positions providing to the swimmers a stable base to rest the rear foot as their preference (Figure 5). This back plate represents a dramatic improvement in the swimming starts performance and the beginning of a new start technique, the kick-start.

Figure 5. Starting block with back plate (OSB11) and kick-start technique.

Many studies based on the analysis of the kick-start agree that the main advantage of this swimming start falls on the block phase. The implementation of the black plate tends to enhance the force developed on the block resulting in a reduction of the time invested on the block and larger horizontal velocities at the instant when the swimmers leave the block. These advantages induce significant improvements because swimmers are able to travel larger distances in the air without increasing the flight time resulting in shorter time to 5, 10 and 15 m (García-Ramos et al., 2015; Nomura et al., 2010; Vantorre et al., 2010a).

The main biomechanical difference between asymmetrical techniques (kick-start and track start) and symmetrical techniques (grab start) is the force developed on the block. The track start and kick-start show a bimodal force profile corresponding to rear foot and front foot. In contrast, the grab start technique shows a single peak force produced previously to the instant when the swimmer’s feet leave the block (Benjanuvatra, Lyttle, Blanksby, & Larkin, 2004; Mason et al., 2007). Studies comparing the grab start and track start showed larger horizontal, vertical and resultant peak forces, higher peak power and average vertical and resultant force for grab start than for track start as consequence of the block pushing with both legs at the same time (Benjanuvatra, Lyttle, Blanksby, & Larkin, 2004; Krüger et al., 2003; Mason et al., 2007; Vantorre et al., 2011; Vantorre, Seifert, Fernandes, VilasBoas, & Chollet, 2010). However, this technique has smaller average horizontal force on the block than the track start. This is because the track start allows to swimmers develop a progressive horizontal force development along the block phase. In contrast, for grab start negative values of horizontal force were observed previously to the instant when the swimmer’s hands leave the block (Arellano, Pardillo, De La Fuente, & García, 2000; Benjanuvatra et al., 2004; Takeda & Nomura, 2006; Vantorre, Seifert, Fernandes, VilasBoas, et al., 2010c).

The back plate implementation leads to an improvement in the asymmetrical techniques due to the increase of the forces developed on the block. The rear foot support increased the stability of the swimmers on the block and the capacity to develop larger forces with the rear leg. Consequently, different studies showed significant larger values in the horizontal and vertical peak force, the average horizontal force as well as in the horizontal and vertical velocity and acceleration at the instant when the swimmer's feet leave the block for kick-start than for track start (Biel, Fischer, & Kibele, 2010; Honda, Sinclair, Mason, & Pease, 2010; Ozeki et al., 2012).

The force development plays an important role on the total time invested on the block and the total start performance. The horizontal take-off velocity is considered the best predictor of the start performance (see section 3) and this variable is dependant on the horizontal impulse (horizontal force × time) developed on the block. Consequently, different studies about the track start and grab start technique suggested that the swimmers must manage the compromise between a long time spent on the block to create more force and a short time on the block to minimize the time deficit (Vantorre et al., 2010c).

Contrary to this conclusion, several results showed shorter time on the block and higher horizontal velocity for kick-start than for grab start and track start (Beretić et al., 2012; Garcia-Hermoso et al., 2013; Honda et al., 2010; Ozeki et al., 2012). In this regard, the implementation of the back plate suggested the reduction of the time invested on the block without sacrificing the horizontal impulse developed (Honda et al., 2010). The back plate increases the explosive force developed on the block reducing the response time after the start signal increasing the development of the horizontal and vertical accelerations (Biel et al., 2010; Honda et al., 2010; Ozeki et al., 2012). In this regard, Slawinski et al. (2010) highlighted the relevance of the rear leg to obtain larger horizontal take-off velocity without increasing the time on the block. These authors observed that the maximum acceleration on the block is reached when the rear foot push on the back plate, in less than 0.15 s. Consequently, swimmers are able to obtain larger temporal advantages and higher horizontal forces before the rear foot leave the block, which let a shorter time on the block and larger horizontal take-off velocity values.

The higher horizontal take-off velocity allows to swimmers cover higher distances in the air in less time using the kick-start (Beretić et al., 2012; Nomura et al., 2010; Ozeki et al., 2012). Moreover, the larger temporal advantages on the block and a similar performance in the entry into the water (Beretić et al., 2012; Ozeki et al., 2012; Vantorre et al., 2011) lead to significant temporal advantages in the time to 5, 7.5, 10 and 15 m time in comparison with the track start and grab start technique (Beretić et al., 2012; Biel et al., 2010; Honda et al., 2010; Ozeki et al., 2012).

The great advantages provided by the back plate and the different configurations of the mobile surface (five different positions) has led to focussed many investigations on the optimal back plate position (Honda et al., 2012). Moreover, many studies have measured different positions of the centre of mass (CoM) on the block analysing three different variants: Neutral-weighted Kick-Start (Neutral kick-start) characterized by a neutral projection of the swimmer's CoM, the Rear-weighted Kick-Start (Rear kick-start) with a rear projection of the swimmer's CoM and the Front-weighted Kick-Start (Front kick-start), which exhibits a front projection of CoM in the starting position (Barlow, Halaki, Stuelcken, & Greene, 2014; Honda et al., 2012; Kibele, Biel, & Fischer, 2014; Slawinski et al., 2010). The results of these studies differ in the biomechanical advantages offered for each back plate position and the CoM positions on the block.

A wide stance of the back plate, those positions further from the edge of the block, was suggested to be optimal to obtain higher horizontal take-off velocity and shorter time on the block. A narrow stance of the back plate, those positions closer to the edge of the block, allowed to develop higher horizontal and resultant peak forces with the rear leg (Honda et al., 2012). However, Kibele et al. (2014) showed larger advantages in the time invested on the block and horizontal peak force with a narrow stance. Similar contradictions were found for the CoM position on the block. Slawinski et al. (2010) indicated that a CoM position closer to the start line (Front kick-start) is important to reduce the displacement of the CoM on the block as well as to create a higher horizontal take-off velocity and shorter time on the block. However, later studies showed shorter time on the block, higher horizontal take-off velocity, longer distance travelled in the air and longer time to 5 and 15 m in Front kick-start than in Rear kick-start (Kibele et al., 2014).

In agreement with Slawinski et al. (2010) and Slawson, Chakravorti, Conway, Cossor, & West (2012), the contradictions in the results of the different back plate configurations and CoM positions could associate to changes in the knee angle (angle formed by the hip, knee and the ankle. See section 3). The knee angle is an important parameter in the block performance because is directly related with the force production at the starting signal (Slawson et al., 2012; Slawson, Conway, Cossor, Chakravorti, & West, 2013). In this regard, for kick-start a rear knee angle approximately at 75-85° and a front knee angle at 135-145° at set-position was shown to be the most effective angles for a shorter time on the block and higher horizontal take-off velocity (Slawson et al., 2012; Slawson et al., 2013). In this line, Slawson et al. (2012) found that swimmers adjusted their body position to accommodate the movement to the different back plate stances obtaining the same knee angle values. Likewise, Slawinski et al. (2010) associated the forward CoM position with a greater rear knee angle. In this regard, a greater rear knee angle was shown to allow a position of the shoulder further fordward and to move the CoM closer to the start position.

3. Biomechanical analysis of the swimming start

Throughout history a lot of studies have been developed to analyse, describe and/or compare different start techniques. These investigations have been always determined by the most popular technique performed by swimmers. In this regard, the first studies including an analisys of swim starts were focussed on the differences and advantages of the conventional start techniques. After the appearance of the grab start, most of the studies described or compared this start technique with the conventional starts. When the use of the conventional techniques starts to decrease and appears the track start technique in 1973, the literature included the grab start and/or track start in their analysis. Nowadays, the kick-start technique is the most popular and the most studied technique. The main objective of these studies was to compare the start techniques looking for the most effective performance for a swim race. Moreover, they were conducted to identify which are the most relevant parameters that determine an optimal start performance. With the purpose to make an optimal biomechanical analysis of the swimming start, the starts are divided in different phases and each phase is analysed separately. For their analysis, several biomechanical variables and different methods of measurement were developed in order to provide numerical results and determine the effectiveness of each technique.

3.1. Phases of the swimming start

For an optimal biomechanical evaluation of the swimming starts, these are divided into the block, flight and water phase (Guimaraes & Hay, 1985). The block phase is defined as the time elapsed between the starting signal and the instant when the swimmer's feet leave the starting block. The flight phase is the time elapsed between the instant when the swimmer's feet leave the starting block and the swimmer's have the first contact with the surface of the water. The water phase is defined as the time elapsed between the first contact with the water and the start of the swimming movement. To improve the analysis of the starts, the water phase was divided into two sub-phases: the glide phase defined as the time elapsed between the first contact with the water and the start of the swimming movement and the underwater leg propulsion phase defined as the time spent between the first kick and the first stroke (Elipot et al., 2009). An early study established that the contribution in percentage of time for each phase of the start at 15 m distance is 11%, 5% and 84% for the block phase, flight phase and water phase, respectively (Slawson et al., 2013).

Later on, a fourth phase was added and the swimming starts were divided into block phase, flight phase, water phase and swim phase. The swim phase was defined as the time following the water phase from the surface breakout to 15 m. With this new phase the contribution of each phase in percentage of time was of 11%, 5%, 56% and 28% for the block phase, the flight phase, the water phase and the swim phase, respectively (Tor, Pease, & Ball, 2014).

3.2. Terminology and definition of the biomechanical variables included in the study of the swimming start

Spatiotemporal, angular, kinematic and kinetic variables were defined for the studies that report an analysis of the swim start techniques. The most important variables involved in the study of a swimming start are explained in detail in this section. Moreover, an appendix section was included containing the several terminologies and definitions used for each variable towards to the end of this thesis.

3.2.1. Spatiotemporal variables

The spatiotemporal variables are those parameters that provide quantitative information about the duration of a determined phase or displacement (temporal variables) as well as information about the distance travelled, longitudes, heights or spatial positions (spatial variables).

The performance of a swimming start is measured by the time that swimmers invest in travel 5, 7.5, 10 or 15 meters. In this regard the shortest time invested from the starting signal until the swimmer's head reach the 5, 7.5, 10 or 15 m is associated with the best start performance.

The time to 5 m is typically used to determine the performance in the block time and flight time. This is because at this distance the underwater undulatory movement is excluded. As the actions performed during the gliding or underwater leg propulsion phases are not dependent on the start technique (Mason et al., 2007), for proficient swimmers the time to 5 m allows to obtain an estimation of the total aerial phase performance, defined as the sum of the block phase and the flight phase.

The time to 7.5 m and 10 m are also used to study the total start performance however, the time to 15 m is the most commonly variable used to determine the effectiveness of a swimming start due to the 15 m distance was established as the swim underwater limit distance (FINA rules SW 7.4).

With the objective to obtain the best start performance, it was supported that the first goal of the swimmers is to react quickly to the starting signal, i.e. shorter reaction time, and leave the block rapidly (shorter movement time) generating as much horizontal velocity as possible (Guimaraes & Hay, 1985). The block time, defined as the sum of the reaction time and the movement time, is one of the most influential variables to obtain the best start performance. Fischer and Kibele (2016) after identifying the significant variables for the swim start phases determined that the block time explains the 92.5% and 96.3% of the variance in the grab start and track start, respectively, considering the time to 7.5 m as the distance of measurement to estimate the effectiveness of the start.

The block time is a relevant variable due to its influence on the generation of horizontal take-off velocity. The horizontal take-off velocity is dependent on the impulse that swimmers generate on the block; larger impulse involves larger take-off velocities and the largest impulse on the block is produced by a largest force and a longest block time (Impulse = force × time). However, as swimmers should invest shortest times on the block after the starting signal, they must find an optimal balance between the longest block time to create larger impulse and a shortest block times to minimize the effect on the total start performance (Seifert et al., 2010; Vantorre et al., 2010a; Vantorre et al., 2010c).

The time invested in the air (flight time) is also an important parameter in the start performance. The flight time explains an 84.3% and 59.8% of the total variance in the grab start and track start, respectively, at time to 7.5 m (Fischer and Kibele, 2016). The longest time invested in the air supposes a shorter time to 15 m (Ruschel, Araujo, Pereira, & Roesler, 2007; Seifert et al., 2010; Vantorre et al., 2010a; Vantorre et al., 2010c). As the air resistance is considered negligible, longer time in the air allows swimmers to maintain the high take-off velocity during more time and in consequence to perform a more efficient start technique (Vantorre, Seifert, Fernandes, Vilas-Boas, & Chollet, 2010b). In agreement with theses results, longer entry time (defined as the sum of block time and flight time) were related with a shorter time to 15 m (Vantorre et al., 2010a; Vantorre et al., 2010c).

Finally, the time spent under the water (underwater time) is considered the most important parameter to obtain an optimal start performance. The underwater time, including the glide time, underwater kicking and swim time, is the longest time taking to account the time spent on the block or in the air (Elipot et al., 2009; Tor et al., 2014). A recent study reported that the underwater time explains a 99% and 98.9% of the total variance in the grab start and track start, respectively, at time to 7.5 m (Fischer & Kibele, 2016). However, as longer entry times imply shorter times to 15 m, reduce the time invested under the water is required to obtain the shortest time to 15 m (Vantorre et al., 2010a; Vantorre et al., 2010c).

Concerning the spatial variables, the most relevant parameter in a swimming start is the flight distance due to its relationship with the time to 15 m. Larger flight distances was related with the best total start performance (shorter time to 15 m) (Ruschel et al., 2007). Although, further relationships has not been shown between the start performance and other spatial variables, many of these variables are important due to its influence on the variables implied in the block phase, flight phase and the good performance under the water.

The horizontal position is a variable commonly used to indicate the projection of the swimmer's CoM at starting position. This variable is mainly measured in the asymmetrical techniques i.e. track start or kick-start (Barlow et al., 2014; Honda et al., 2012; Kibele et al., 2014; Slawinski et al., 2010; Vilas-Boas, Cruz, Sousa, Conceição, & Carvalho, 2000; Slawinski et al., 2010; Slawson et al., 2012). The rear foot allows swimmers three different CoM positions on the block with different results on the swim start performance: a rear projection of the swimmer's CoM, which involves larger horizontal position values; a front projection of the swimmer's CoM, resulting in smaller horizontal position values; or a neutral projection of the swimmer's CoM with horizontal position values between those obtained in the rear and front projection. Especially for the track start technique, a rear CoM projection was related with larger CoM displacement on the block and also with shorter reaction times, longer times invested on the block (block time) and longer time in the air (flight time). Moreover, this position induces a higher vertical and horizontal impulse, higher horizontal take-off velocity and higher loss of velocity under the water leading to larger total start time, measured as the time invest between the starting signal to the last pixel visible (6.07 m) (Vilas-Boas et al. 2000). As was explained in the section 2, for the kick-start technique the different CoM positions were associated to the differences in the knee angle due to changes in the knee angle that imply a displacement of the CoM. In this regard, several contradictions were shown between the different CoM positions at the starting position and the kick-start performance (Slawinski et al., 2010; Slawson et al., 2012). For example, Slawinski et al. (2010) indicated that a CoM position closer to the start line is important in reducing the displacement of the CoM on the block as well as in creating a higher horizontal take-off velocity and shorter block time. However, later studies showed lower block time, horizontal take-off velocity and flight distance as well as longer time to 5 m and 15 m with a front projection of CoM in the set position than with a rear position of the CoM (Barlow et al., 2014; Honda et al., 2012, Kibele et al., 2014).

Finally, the diameter of the entry hole made when the body enters into the water (entry hole) and the maximum depth reached under the water (maximum depth) were shown two relevant variables to obtain an optimal water entry and consequently the best performance under the water and the best total start performance (Mason, Franco, Sacilotto, & Hazrati, 2014; Tor, Pease, & Ball, 2015b, 2015c). The entry hole determines the type of water entry, such as higher values of entry hole were related with a flatter entry, which causes a faster deceleration under the water. In contrast, smaller entry hole values leave a pike entry (to enter the water through one spot) and the swimmer will decelerate less rapidly under the water (Maglischo, 2003). Likewise, the maximum depth reached under the water is a relevant variable as a consequence of its influence on the drag force and the average velocity of the underwater phase (Elipot et al., 2009). Higher depth reduces the resistance that acts on the swimmers when they are moving through the water (drag force) and allows them to maintain higher average velocities under the water.

3.2.2. Angular variables

The angular variables are used to define the amplitude between two body segments, the body orientation in a certain instant or the segments position between them. Typically, the angular variables are defined or by three anatomical points or one vector and two anatomical points or two vectors. For example, knee angle is defined by three anatomical points; the hip, the knee and the ankle anatomical points; the entry angle by one vector and two anatomical points; the horizontal axis and the hip and finger tip anatomical points; and the take off angle by two vectors, the resultant velocity vector and the horizontal axis.

In the swimming starts, although the angular variables are not directly related with the time to 5, 7.5, 10 or 15 m, they determine the results of several parameters related with the start performance. The take-off angle and entry angle are the most used angular variables to describe or to compare the swimming starts. These angles determine the body position relative to the water surface. Typically, a positive take-off angle is associated with an upward body direction, in contrast negative values are related with a downward direction. Similar associations are made with the entry angle. Larger entry angle values are associated with a higher vertical CoM position at water entry and smaller entry hole values (pike entry) and lower values indicate a lower vertical CoM position and higher entry hole (flat entry). These angular variables are related between them; higher take-off angle lead to larger entry angle values. Moreover, higher take-off angle also implies longer time in the air (longer flight time) and shorter time to 15 m (Seifert et al., 2010). The entry angle was shown to have a direct impact in the performance under the water because it has influence on the depth of the gliding phase (Elipot et al., 2009).

Other relevant variables concerning to the entry into the water are the angle of attack and the hip angle (appendix 2) (Fischer & Kibele, 2014; Ozeki, Sakurai, & Taguchi, 2008). Similarly to the entry angle, the angle of attack and the hip angle represent the body posture at the first contact with the water. Smaller angle of attack and larger hip angle were related with shorter time to 7.5 m and 15 m (Fischer & Kibele, 2010a; Ozeki et al., 2008). Fischer and Kibele (2014) showed that an hyperextended back position at water entry (larger hip angle) allows to swimmers to prepare a powerful dolphin kick after the feet enter into the water decreasing the loss of velocity produced because of the water entry.

The shoulder angle was measured at the starting position, take-off and water entry (Seifert et al., 2010; Vantorre et al., 2010; Vantorre et al., 2011). This angular parameter indicates the arms displacement of the swimmers during the start. In this regard, higher shoulder angle was related with the arms position in continuation of the body, in contrast, smaller values are associated with a forward displacement and negative values are associated with an arms placed behind the trunk (Vantorre et al., 2010).

Concerning the knee angle and ankle angle, these variables were measured mainly in the kick-start technique. This is because both parameters were associated with the ability to develop force with the rear foot and the front foot on the block (Beretić et al., 2012; Nomura et al., 2010; Slawinski et al., 2010; Slawson et al., 2012).

3.2.3. Kinematic parameters

The kinematic variables are those that study the trajectory of the body as function of time. In this regard, velocity and acceleration are the main magnitudes included in a kinematic study. In swimming starts, the horizontal take-off velocity and the average horizontal acceleration are the best predictors of the start performance (García-Ramos et al., 2015; Tor et al., 2015b).

The horizontal take-off velocity represents the 81% of the variance in a start performance (time to 15 m). This parameter depends on the horizontal impulse and the body mass. The horizontal impulse is calculated as the horizontal force applied on the block by the time. Therefore, larger horizontal force and larger block time lead larger horizontal take-off velocity values (García-Ramos et al., 2015). Consequently, as was explained in the temporal variables section, the fact that the main objective in a swim start is to get the shortest time, the swimmers must find an optimal balance between the longest block time to create larger impulses and a short block time to minimize the effect on the total start performance (Vantorre et al., 2010b; Vantorre et al., 2010c).

The horizontal take-off velocity was associated with the time invested in the air (flight time), the distance travelled in the air (flight distance), the horizontal velocity at water entry, the entry angle and the start performance. Larger horizontal take-off velocity values allow swimmers to travel larger distances in the air in less time and reach the water with higher horizontal velocity (higher horizontal velocity at water entry), in consequence the result is a shorter time to 5, 10 and 15 m. In spite of the higher horizontal take-off velocity implies lower entry angle (flatter entry) (Alptekin, 2014; García-Ramos et al., 2015; Nomura et al., 2010; Vantorre et al., 2010b).

Besides the horizontal take-off velocity, the average horizontal acceleration on the block is a good predictor of the start performance. This variable it is associated with the force developed on the block and the ability to produce this force quickly. In this regard, the largest average horizontal acceleration values allow to swimmers to obtain higher horizontal take-off velocity without any lost of time on the block. Consequently, larger average horizontal acceleration was related with shorter time to 5, 10 m and 15 m (García-Ramos et al., 2015).

The vertical and resultant velocity and acceleration components have not been considered relevant in the start performance. Larger vertical take-off velocity values imply higher height at take-off, flight time and the entry angle (Alptekin, 2014; Kollias, Baltzopoulos, Chatzinikolaou, Tsirakos, & Vasiliadis, 1990). Consequently, larger vertical take-off velocity values are associated with a more upward position at take-off and leads longer flight time and larger entry angle. In contrast, smaller values indicate a downward position at take-off, shorter flight time and a flatter entry. Concerning the resultant take-off velocity, due to the relationship between the horizontal take-off velocity and the time to 5, 10 and 15 m, similar relationship was shown for this parameter (García-Ramos et al., 2015). At entry water, the higher vertical velocity was associated with a lower entry angle and the resultant velocity at water entry was negatively correlated with the time to 5 m (Alptekin, 2014; Arellano, Pardillo, De La Fuente, & García, 2002).

Under the water, the most relevant kinematic parameter that influences the start performance is the underwater velocity. A significant negative correlation was reported between the average underwater velocity and the time to 15 m (Ruschel et al., 2007). Consequently, the main objective for swimmers under the water is to maintain the velocity obtained on the block as long as possible avoiding an important loss of velocity (Tor et al., 2015a). The underwater velocity has been shown to be affected by the drag force, the depth reached after entering into the water, the entry angle and the average velocity during the gliding (Elipot et al., 2009; Fischer & Kibele, 2016; Tor et al., 2015a). This is because the drag force is the resistance that acts on a swimmer when they are moving through the water and it is affected by the depth reached after entry into the water (Tor et al., 2015a). Likewise, the entry angle and the average velocity during the gliding have been shown to affect the depth and the drag forces, respectively (Holthe & McLean, 2001; Miller, Allen, & Pein, 2002).

Angular momentum produced at take-off as well as the body rotation during the flight is also an important parameter for the best start performance. This is because this parameter has a great influence on the water entry (McLean, Holthe, Vint, Beckett, & Hinrichs, 2000; Vantorre et al., 2010; Vantorre et al., 2011). Due to that, the analysis of the angular momentum in the swimming start is the main objective of this thesis, this parameter will be described in detail in below.

3.2.4. Kinetic variables

The kinetic variables are those parameters related with the forces required to generate the acceleration that a stopped body needs to start a movement.

In swimming starts, as a consequence of the great relevance that horizontal take-off velocity and average horizontal acceleration have on the start performance, the horizontal force developed on the block is essential for an optimal swimming start. In this regard, largest horizontal impulse was related with shorter time to 5, 10 and 15 m (Arellano et al., 2000; Benjanuvatra, Edmunds, & Blanksby, 2007; García-Ramos et al., 2015; Vantorre et al., 2010b; West, Owen, Cunningham, Cook, & Kilduf, 2011). For the vertical force component (average vertical force, peak vertical force and vertical impulse), the relevance in the start performance differed depending on the start technique analysed. Studies including the track start showed this parameter not related with the start performace (García-Ramos et al., 2015; West et al., 2011). In contrast, Slawson et al. (2013) suggested that a better kick-start performance with respect to block time, take-off velocity and entry distance are dependant on high peak vertical forces. Few contradictions were found for the grab start technique. Benjanuvatra et al. (2007) not showed the vertical impulse relevant for the best time to 5 and 15 m in elite swimers. On the contrary, recently, Mourão et al. (2015) highlighted the relevance of the vertical force in the grab start performance.

The power and the work developed on the block were associated with the optimal ability to leave the block (Mason et al., 2007). This is because these variables are calculated from the force development on the block. The peak power is defined as the instantaneous force multiplied by the velocity and the work is the integral of power multiplied by the time.

Concerning to the rate force development, recently was demonstrated that this parameter has been shown an extremely importance in the ability to leave the block at a high velocity in the kick-start technique (Slawinski et al., 2010). An increase in the rate of force development means a great increase in the level of muscle force in the early phase of muscle contraction. Consequently, the highest rate of force development was associated with great levels of force development in shorter time. However, this variables were only included in one study about swimming starts (Slawinski et al., 2010).

3.3. Methods for measuring biomechanical variables in the swimming start

In swimming, the data collection supposes a number of technical issues due to the aquatic environment where the trials are developed. To obtain the quantitative results of the spatiotemporal, angular, kinematic or kinetic variables in swimming starts, there are two main methods for the data acquisition and data processing: the cinematography and the force plates.

The cinematography is the most commonly method for the data acquisition in swimming starts. This method permits to obtain temporal and spatial variables as well as different magnitudes coming from these variables (angular and kinematic variables). The cinematography procedure consists in the recording of different trials performed by swimmers and the subsequent video analysis to calculate the quantitative variables.

In swimming starts, the temporal variables are acquired by a multi digital cameras setup. These cameras are positioned along the trajectory of the swimmers to capture the different positions and the displacement of the participants along each phase. With the objective to establish the instant at starting signal, a trigger sound, audible to the swimmers and visible from each camera with a flashing light is required in this method.

Obtaining spatial, angular or kinematic variables requires, besides the cameras arrangement make necessary the use of a calibration volume that permits to obtain the real coordinates of a determined anatomical point. Typically, the calibration volume is a static structure with knowledge and similar dimensions to the space travelled by swimmers (Figure 6, 7). This structure has a certain number of control points which are distributed on calibration volume with a known coordinates (control points are identified in red in the figure 6). Before to start the trials recording, this calibration volume is positioned on plane to the motion of swimmers and it can be registered simultaneously for each camera. With this process, the coordinates of the calibration points are registered in each camera allowing, after the recording and by a manual or automatic tracking, a movement reconstruction and the elimination of the errors associated to the digitalization or to the image distortion through the use of the direct linear transformation algorithm (DLT) (Abdel-Aziz & Karara, 1971).

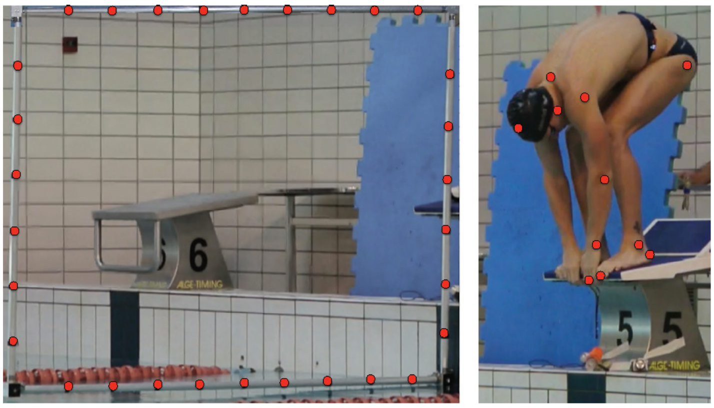

Figure 6. Calibration volume for a 2D analysis with the control points identified in red and anatomical points in red for a 2D analysis based on the method of de Leva (1996).

Manual tracking is the most used method to detect the calibration points and follow the trajectory of anatomical body landmarks. As a consequence of the complexity of the calibration process and posterior anatomical body landmarks tracking, the two-dimensional (2D) data collection is the most commonly method using in the recording of swimming starts. A 2D data collection implies the tracking on one side of the body (assuming the existence of a bilateral symmetry); and it can be recording with just one camera (Figure 6). In contrast, a 3D data collection required the tracking of two sides of the body and the use of minimum two cameras in the trial recording (Figure 7) (de Jesus et al., 2015).

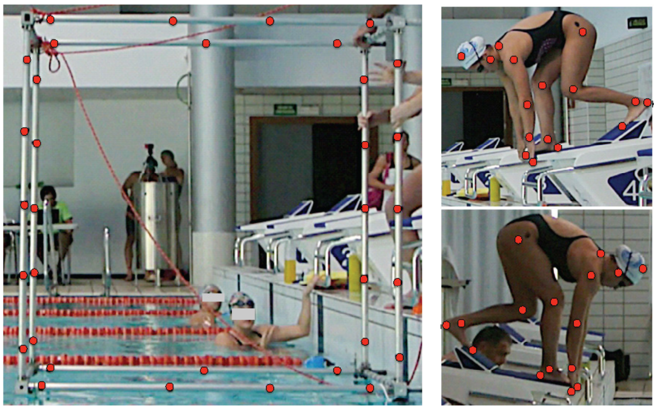

Figure 7. Calibration volume for a 3D analysis with the control points identified in red and anatomical points in red for a 3D analysis based on the method of de Leva (1996).

The acquisition of the kinetic variables is made through the use of the force platforms method. These force platforms are placed on the block to measure the ground reaction force developed during the block phase. Moreover, this system is often used to determine the temporal variables, mainly the reaction time and block time. The force platforms permit to establish the instants of the first movement by the change in the ground reaction force provided by the platform. Likewise, when the ground reaction force drop to zero values indicates the take-off instant.

THE ANGULAR MOMENTUM

1. Theoretical basis of angular momentum

The *angular momentum* (H) is a mechanical factor that makes the athlete rotate (Dapena, 2000). It is determined by the product of the *momentum of inertia* (I) and the *angular velocity* (ω) of a body or body segment (Equation 1).

$$H\ (\mathrm{kg.m^2/s}) = I\ (\mathrm{kg/m^2})\ \mathrm{x}\ \omega\ (\mathrm{radians/s}) \qquad (1)$$

Momentum of inertia (I) is the reluctance of a body to begin rotating or to change its state of rotation about an axis. It is referred to the body's ability to resist rotation and it is determined by the body mass (m) and the distance between the axis of rotation and the body CoM (r) (Equation 2). The angular velocity (ω) is the angular displacement (θ) divided by the time spent on this displacement (t) (Equation 3).

$$I\ (\mathrm{kg/s^2}) = m\ (\mathrm{kg})\ \mathrm{x}\ r^2\ (\mathrm{m^2}) \qquad (2)$$

$$\omega\ (\mathrm{radians/s}) = \theta\ (\mathrm{radians})\ \mathrm{x}\ t\ (\mathrm{s}) \qquad (3)$$

The angular momentum is related to a particular axis of rotation that can be separated into three orthogonal components: 1) angular momentum about the mediolateral axis (Hx) is mainly responsible for the somersaulting rotation of the athlete, 2) angular momentum about the sagittal axis (Hz) which is mainly responsible for the twisting rotation of the athlete of the standards; and, 3) angular momentum about the anteroposterior axis (Hy) that also produces a somersaulting rotation of the athlete (Dapena, 1980). Consequently, the angular momentum of the whole body is the sum of the angular momentum for each body segment that is acting about the same axis of rotation (Equation 4) (Dapena, 1978; Hay, Wilson, & Dapena, 1977).

The angular momentum of each body segment (H_i) is the sum of a *remote angular momentum* (H_{remote}) and a *local angular momentum* (H_{local}) (Equation 5). H_{remote} is defined as the angular momentum development for each body segment respect to the axis of rotation of the CoM of the segment. And, H_{local} is the angular momentum of each segment respect to the axis of rotation of the body CoM.

$$H = \Sigma H_i \tag{4}$$

$$H = \Sigma \, (H_{remote} + H_{local})_i \tag{5}$$

$$H = \Sigma \, (m_i \, . \, r_i \, . \, v_i + I_i \, . \, \omega) \tag{6}$$

The Newton's laws are applicable to the angular motion, which explain how torques create rotation. In angular terms these laws can be reworded as follow (Grimshaw, Lees, Fowler, & Burden, 2007):

Newton's first law

The angular momentum of a body remains constant unless a net external torque is exerted upon de body.

Newton's second law

When a torque acts on an object the change in angular motion (angular momentum) experienced by the object takes place in the direction of the torque, and this is proportional to the size of the torque and inversely proportional to the moment of inertia of the object.

Newton's third law

> Whenever an object exerts a torque on another there will be an equal and opposite torque exerted by the second object on the first.

The amount of angular momentum is dependant on the external force acting on a body. In this regard, the athlete obtains angular momentum during the take-off phase, through the forces that body segments make against the ground (action force) (Newton's first law) and that the ground back or reacts with a force equal in magnitude but opposite in direction (reaction force) (Newton's third law) (Dapena, 2000).

The force by which the athlete creates rotation is the *momentum of force* or *torque* (T). This torque is the product of the magnitude of the force (F) and the perpendicular distance from the CoM to the line of action of the force known as moment arm (l) (Equation 7) (Knudson, 2003). Besides the torque, the variation of the angular momentum or angular impulse is also dependant on the time of application of this torque (Equation 6). Consequently, the angular momentum is created through the force developed by the athlete (F), the moment arm (l) and the time over which the rotational force is acting (t) (Equation 7).

$$H_{(kg.m^2/s)} = T_{(N.m)} \times t_{(s)} \tag{7}$$

$$H_{(kg.m^2/s)} = F_{(N)} \times l_{(m)} \times t_{(s)} \tag{8}$$

Since the instant when the athlete is applying torque, he/she is creating rotation with a determined velocity, direction or both. The rate at which the angular velocity or the direction of the body is changed is defined as angular acceleration (α) and is represented as the change in angular velocity divided to time it took for the change. In this regard, when a large change in angular velocity occurs in a short period of time, the angular acceleration will be large.

The angular acceleration of a body is directly proportional to the torque applied and inversely proportional to the momentum of inertia of the body (Newton's second law) (Equation 8). As large torque and small momentum of inertia values increase the angular acceleration, this involves a large change in angular velocity in a short period of time. As was mentioned above, an increase in the angular impulse (or variation of angular momentum) is dependant on large application of torque during long time. With this objective the athlete must increase the momentum of inertia in order to reduce the angular acceleration and consequently increase the time of application of torque (Kreighbaum & Barthels, 1990).

$$\alpha \text{ (rad/s}^2\text{)} = T \text{ (N.m)} / I \text{ (kg/s}^2\text{)} \qquad (9)$$

The way in which the ground reaction force acts upon the athlete during the take-off to influence angular momentum with respect to the body CoM determines the rotational direction of somersault (Newton's second law). The line of action of the ground reaction force with respect to the CoM determines entirely the rotational direction of somersault. A rotation in an anticlockwise direction is produced if the line of action of the reaction force passes in front of the CoM throughout the most of take-off. In contrast, when the line of action of the reaction force passes behind the CoM throughout the most of take-off is produced a rotation in a clockwise direction. Typically both directions are associated with the positive sign and negative sign, respectively. Moreover, if the line of action of the reaction force passes directly through the CoM will have zero moment of force or torque and will not be able to produce any change in angular momentum with respect to the CoM (Grimshaw et al., 2007).

After the athlete leaves the ground the path of CoM angular momentum is totally determined, and there is nothing that the athlete can do to change it (Dapena, 2000). The total angular momentum possessed by the body in the absence of any external force remains constant (conservation of angular momentum principle) (Newton's first law). In this regard, assuming that air resistance is negligible, the angular momentum of the athlete with respect to the CoM remains constant throughout the flight. However, along the flight phase and based on the amount of angular momentum obtained at take-off instant, the athlete can move one part of the body in one direction and other parts in the opposite direction with the objective to increase or reduce the rotational velocity and change the body position (Dapena, 2000).

As was mentioned above, the momentum of inertia of a body is related to a specific axis of rotation and the body mass (Equation 2). In this regard, as the mass is constant, athletes must to chance the distribution of this mass about a determined axis to increase or decrease the momentum of inertia. Athletes will be able to reduce the momentum of inertia if they distribute the mass much closer to the axis of rotation. On the contrary, the momentum of inertia will be increased when the mass is place away from the axis of rotation. Since the angular momentum is determined at take-off instant and must remains constant along the flight phase, changes in the momentum of inertia must produce changes in the angular velocity. If athletes reduce the momentum of inertia the angular velocity will increase and they will be able to perform more somersault in a short space of time. In contrast, if athletes wanted to enter the water in a straight and controlled position they would straighten the body and increase the momentum of inertia with the consequence reduction of their rotation (reduce the angular velocity).

2. Angular momentum in the swimming start

The water entry was suggested to be the first relevant factor in order to obtain an optimal start performance (Mason et al., 2007). This is because it has a direct impact on the water phase performance.

In swimming starts, the water phase is considered decisive in order to achieve and efficient start. This is the largest phase (the time percentage of contribution is approximately 56% in time to 15 m) and is when the swimmers reach the faster velocities through the water (Elipot et al., 2009; Tor et al., 2015b). Several studies reported that this phase represents the 94%, 99% and 96% of the total variance in swim start time to 7.5 m, 9 m and 15 m respectively (Fischer & Kibele, 2016; Guimaraes & Hay, 1985; Tor et al., 2015b).

The main objective along the water phase is to maintain as long as possible the velocities created on the block and during the flight phase (Elipot et al., 2009). The underwater velocity is considered a relevant parameter to reduce the water time and to obtain an optimal start performance. This variable is dependant on the average horizontal velocity at water entry and the drag force (resistance acting to decelerate the swimmers) acting on swimmers. Consequently, the greatest horizontal velocity at water entry and the less drag forces, the greatest average underwater velocity (Guimaraes & Hay, 1985).

The drag force increases linearly with the speed and when the swimmers travel closer to the water surface. Therefore, with the objective to minimize the drag force experienced under the water to avoid an excessive loss of velocity it was recommended that swimmers must achieve a depth of approximately -0.92 m under the water (Tor et al., 2015a). However, in spite of drag force increase with large horizontal velocity, it was suggested that largest horizontal velocity at water entry slightly more help than hindrance (Guimaraes & Hay, 1985).

The depth achieved under the water depends on the entry position into the water. Moreover, the water entry also plays and important role in the maintenance of the horizontal velocity. A pike entry will reduce the drag at the point entry while the flat entry causes to decelerate rapidly because the body strikes the water in several places at once (Maglischo, 2003). Moreover, recently it was reported that a hyperextended back at water entry (large angle of attack and large entry hole) minimize the loss of horizontal velocity because contributes to prepare a powerful dolphin-kick after the feet enters into the water (Fischer & Kibele, 2010a; Fischer & Kibele, 2014).

The swimmers' projection to the water entry is related with the horizontal take-off velocity, take-off angle, flight time and angular momentum (Fischer & Kibele, 2010b; Seifert et al., 2010; Tor et al., 2015b; Vantorre et al., 2010). The angular momentum is considered the most relevant parameter in the body position at water entry. This is because the body rotation development along the flight phase as a consequence of the amount of angular momentum obtained on the block permits to swimmers change their body position to enter into the water (McLean et al., 2000; Vantorre et al., 2010; Vantorre et al., 2011). Despite its relevance, nowadays only three studies in ventral techniques reported data about the amount of angular momentum at take-off (McLean et al., 2000; Vantorre et al., 2010; Vantorre et al., 2011). Table 5 shows a summary about these studies including sample size and level, objectives, main results and conclusions.

Vantorre et al. (2010) after analyse the grab start in five elite male swimmers found three different start styles; flat start, pike start and Volkov start. As was mentioned above, the flat start and pike start are two different styles to enter into the water. In the flat start the body swimmers strikes the water in several places at once, while in the pike start the swimmers enters the water through one spot (Maglischo, 2003). In contrast, the Volkov start is a style start characterized by a backward and forward arm swing.

Significant biomechanical differences were found between the three start techniques. Larger flight time and longer flight distance and take-off angle were reported for pike and Volkov start in relation to the flat start. In contrast, flat start showed longer shoulder angle and horizontal impulse than pike and Volkov start. Further significant differences were reported in angular momentum at take-off (transversal axis) with larger values for pike start and Volkov start than for flat start (14.7 ± 2.92 $kg.m^2/s$; 18.0 ± 0.67 $kg.m^2/s$; 17.5 ± 0.4 $kg.m^2/s$; flat start, pike start and Volkov start respectively). Moreover, larger mean standard deviation for the angular momentum (transfer of angular momentum from the transversal axis) was shown for pike start and Volkov start (0.8 ± 0.13 $kg.m^2/s$; 1.1 ± 0.2 $kg.m^2/s$; 1.1 ± 0.15 $kg.m^2/s$; flat start, pike start and Volkov start respectively). In spite of the entry angle did not show statistical significance; slightly differences were observed between three techniques (23.4 ± 2.2°; 24.6 ± 4.8°; 28.2 ± 2.5°; flat start, pike start and Volkov start respectively).

McLean et al. (2000) showed larger angular momentum values about the transversal axis with asymmetrical techniques than with symmetrical starting positions. After analysing different relay starts (Figure 6) in a group of ten collegiate males found a consistent increase of body rotation as step on the block increased. No-step start presented slightly smaller angular momentum values and shorter body rotation along the flight phase than the other relay starts.

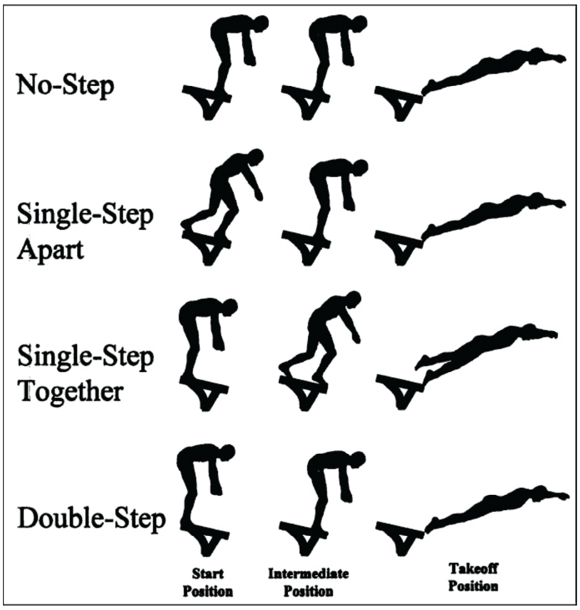

Figure 6. Description of the different relay starts analysed by McLean et al. (2000). Figure exported of McLean et al. (2000) study.

Similar results were reported between the grab start and track start techniques. Vantorre et al. (2011) after analysing a sample of five expert male swimmers found significantly higher angular momentum at take-off (transversal axis) for track start than grab start. Moreover, significantly differences were also showed in the legs angular momentum and mean standard deviation for the angular momentum at take-off with larger values in the track start technique.

During the flight an angular momentum produced by the impulse of the feet in the take-off induces a change in the body orientation by a rotary movement of the legs in the transverse axis (McLean et al., 2000; Vantorre et al., 2011). For asymmetrical techniques larger angular momentum values at take-off allow to swimmers higher changes in the momentum of inertia and/or angular velocity by longer displacements of the lower limbs. Consequently asymmetrical techniques allow to swimmers a body position at water entry slightly steeper which was suggested more favourable for the start performance (McLean et al., 2000; Vantorre et al., 2011).

Table 5. Summary of the papers analysing angular momentum on swimming start techniques.

Author	**Sample**	**Start technique**	**Objective**	**Results and conclusion**
McLean et al. (2000)	10 collegiate males	No-step start Single-step apart Single-step together Double-step	To compare three step starts to the conventional technique (no-step start). To evaluate the effect of restricting step length to 50% of the full step length on performance of three step starts.	Double step start obtained higher speed at take-off and at entry. Step-start techniques showed slightly greater body rotation than no-step start. This greater body rotation was consequence of higher angular momentum at take-off and similar momentum of inertia along the flight phase. Step-start techniques also showed a more upward body position at take-off. However, similar steeper entry orientations were observed at water entry than the no-step start. *Conclusion:* Angular momentum was greater when using step-starts. This allowed entry angles and entry orientations similar to the no-step start in spite of these techniques showed more upward body orientation at take-off. The increased rotation was due to changes in angular velocity and momentum of inertia along the flight phase.
Vantorre et al. (2010)	5 elite males	Grab start	To analyse how the start style influences angular momentum.	Flat start was characterized by lower take-off angle, shorter flight phase and lower angular momentum and mean standard deviation. Pike start and Volkov start opposite results. *Conclusion:* less rotation generated during impulsion induced a flat aerial trajectory and permitted to reach the water earlier. The forward arm swing in the pike start and the backward and forward displacement of the arms in the Volkov start increased the quantity of rotation.
Vantorre et al. (2011)	5 experts males	Grab start Track start	To compare kinetics, body angles and angular momentum during the swimming start for preferred and no-preferred technique.	Larger angular momentum of the legs, total angular momentum and mean standard deviation of angular momentum was obtained for track start than grab start. Grab start showed larger vertical impulse values. *Conclusion:* the asymmetry in the track start technique permits longer legs movement in aerial phase and larger total angular momentum but also larger twisting effect (loose of angular momentum body axis).

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AIMS

The general objective of this thesis has been to study the kick-start performance through the analysis of the development of angular momentum,. As a consequence of the great relevance of the angular momentum on the start performance, it was highlighted the advantages that angular momentum and the body rotation provide to the kick-start. With this purpose, different studies and methodologies were performed. The aims of each study define the specific objectives of this thesis:

1. To determine the biomechanical differences between the kick-start and grab start techniques with the aim to define the key characteristics of the best kick-start performance (chapter 1, section 1.I).

2. To define the relationships among the aerial phase parameters of kick-start in order to analyse the notable factors needed for the best kick-start performance during the aerial phase (chapter 1, section 1.I).

3. To analyse the mechanics of rotation for kick-start and grab start along the aerial phase with the aim to understand the angular momentum contribution in the body rotation and the differences between symmetrical and asymmetrical techniques (chapter 1, section 1.II).

4. To analyse the time-course of the normalized angular momentum about the mediolateral body axis on the block during the kick-start to identify different take-off strategies (chapter 2, section 2.I).

5. To examine the effects of angular momentum on the block on the performance in the different phases of the kick-start technique (chapter 2, section 2.I).

6. To evaluate qualitatively the development of angular momentum about the mediolateral body axis from the block to the glide phase during the kick-start. With this purpose different strategies of angular momentum were described relative to the speed and the body angles adopted (chapter 2, section 2.II).

Biomechanical advantages of the kick-start technique during the aerial phase

CHAPTER 1

INTRODUCTION

With the main objective of finding a technique more beneficial to swimmers, the swimming start has always been in continuous development. The most recent breakthrough in the field of swimming starts appeared in 2009 when the International Swimming Federation (FINA) approved a new starting block with a back plate (FR 2.7 Starting Platforms in FINA's rules) that features an "adjustable, slanted footrest" which led to a new swimming start called kick-start. This starting block modification induced changes in the start technique compared with the previous standards, the grab start or track start. All the studies evaluating this new start technique, called kick-start, have reported important advantages regarding the take-off velocity, block time, flight time and time to 5 m, 7.5 m, 10 m and 15 m compared with the track start technique (Beretić, Durović, Okičić, & Dopsaj, 2012; Honda, Sinclair, Mason, & Pease, 2012; Nomura, Takeda, & Takagi, 2010; Ozeki, Sakurai, Taguchi, & Takise, 2012). However, only two studies included the grab start in the analysis. The authors showed significant higher horizontal take-off velocity and shorter time to 7.5 for the kick-start technique (Biel, Fischer, & Kibele, 2010; Murrel & Dragunas, 2012).

Focussing on the feet position, the grab start is the most opposite technique to the kick-start. Grab start is characterized by a symmetrical starting position, with both feet on the front of the platform. This technique has coexisted for more than forty years with the track start technique due to the disagreements over their advantages and disadvantages. Several authors did not give priority to the use of one technique over the other, concluding that the best start is the most practiced by the swimmers and in which they are specialized (Blanksby, Nicholson, & Elliot, 2002; Jorgić et al., 2010; Mason, Alcock, & Fowlie, 2007; Thanopoulos et al., 2012; Vantorre, Seifert, Fernandes, Vilas-Boas, & Chollet, 2010a). However, other investigations gave preference to the track start over the grab start (Holthe & McLean, 2001; Issurin & Verbitsky, 2002) or the opposite (Ayalon, Van Gheluwe, & Kanitz, 1975; Counsilman, Counsilman, Nomura, & Endo, 1986; Krüger, Wick, Hohmann, El-Bahrawi, & Koth, 2003; Zatsiorsky, Bulgakova, & Chaplinsky, 1979).

In spite of the contradictories results about the differences between the grab start and track-start, the new starting block and the above mentioned biomechanical advantages for kick-start over track start supposed the decline in the grab start for the competitions over the last years and caused that few studies compared the kick-start and grab start. However, certain research studies about the differences between kick-start and grab start are interesting to establish the reasons of the superiority of an asymmetrical technique with the back support (kick-start) over a symmetrical technique (grab start).

After the introduction of kick-start, most of the studies focused their investigations on the block phase performance, and there were no studies providing a detailed analysis of the overall aerial phase. The aerial phase performance, which includes the block phase and the flight phase, was considered important to obtain an optimal swim start performance because of the high contribution of the aerial phase in the water phase performance. Taking into account that the water phase performance is quantitatively measured by the time invested under the water (underwater time), recently, have been demonstrated that the underwater time represents a 99% of the total variance in the swim start time (start signal to 7.5 m beyond the block) for the grab start technique and a 98.9% for the track start technique (Fischer & Kibele, 2016). An optimal water phase performance was shown dependent on the horizontal velocities generated during the block phase and flight phase (Lyttle & Benjanuvatra, 2005; Tor, Pease, & Ball, 2014) as well as the take-off angle and the entry angle (Elipot et al., 2009; Holthe & McLean, 2001; Miller, Allen, & Pein, 2002).

On the block, the horizontal take-off velocity and the average horizontal acceleration were reported to be the most influential parameters for the best swim start performance

(García-Ramos et al., 2015; Tor, Pease, & Ball, 2015). Concerning to the flight phase; the flight distance was considered the most relevant parameter due to its relationship with the total start performance (time to 15 m--flight distance; r = -0.48) (Ruschel, Araujo, Pereira, & Roesler, 2007). Moreover, the body rotation during the flight phase was also shown to be an important parameter in the study of swimming starts. The angular momentum at take-off and the rotational movement during the flight phase affect to the body position at water entry (McLean, Holthe, Vint, Beckett, & Hinrichs, 2000; Vantorre et al., 2010; Vantorre et al., 2011). This is because the angular momentum about the mediolateral axis produced at take-off determines the swimmer's angular velocity during the flight phase and thus the entry angle and entry orientation in the water (McLean et al., 2000).

In spite of the relevance of the angular momentum, it is interesting to note that only a few studies include this parameter in their analysis and they only considered the grab start, track start and the different types of relay starts in their analysis. None of the studies about kick-start performance included rotational parameters in their analysis. Consequently, we performed two different studies analysing the advantages of the kick-start technique paying special attention to rotational parameters.

The first study is focused on the analysis of the advantages on the block and along the flight phase during the kick-start technique. In this study, an analysis about the relationship among the parameters involved on the block and in the air was also included with the aim to provide the relevant variables to improve the kick-start performance. In the second study, we made a detailed analysis about the angular momentum produced on the block and the body rotation of the swimmers along the flight phase. This study includes an analysis of the centre of mass (CoM) angular momentum and the angular momentum in each body segment from the starting signal until the hands make contact with the water.

For both studies, an elite swimmers sample was analysed and the cinematographic method using a 3D DLT data collection and a manual tracking was performed to obtain the quantitative results of each variable included. Moreover, in spite of nowadays swimmers do not use frequently the grab start technique the different position of the feet make appropriate a comparison between both techniques. Consequently, this comparison has been included in both studies.

1.I. Determination of the biomechanical advantages of the kick-start compared with the grab start and the relationship among the aerial phase variables for the kick-start technique

The purpose of this study was to determine the biomechanical differences between the kick-start and grab start techniques with the aim to define the key characteristics of the best kick-start performance. Based on previous studies (García-Ramos et al., 2015; McLean et al., 2000; Slawinski et al., 2010; Tor et al., 2015; Vantorre et al., 2011), we further hypothesized that the best performance in the aerial phase will be related to the block phase parameters (horizontal acceleration and horizontal velocity) and the body rotation during the flight phase. Moreover, angular momentum was expected to be one of the most relevant parameters. In order to reach the aims purposed, sixteen elite swimmers were used in this study. Each one performed a kick-start and grab start with maximal effort until 5 m past the starting block. Agreed with early literature and with the results waited initially, the present study suggested that swimmers must improve the explosive muscle contraction and increase the flight phase duration to improve the kick-start performance during the aerial phase.

a. Methodology

Participants

Sixteen elite members from the Spanish national swimming team (70.7 ± 8.2 kg; 178.7 ± 9.7 cm; 24.9 ± 4.3 years) participated in this study. The FINA points score was calculated according the best time in the main event for each swimmer. The competitive level of the participants was 766.95 ± 124.4 FINA points. Participants preferred the kick-start technique; however, they previously competed and trained with grab start. Therefore, all participants were familiar with performing kick-start, as well as grab start, on the OSB11 start block during training and competition. The participants signed an informed consent and the University Ethics Committee approved the procedures used for this analysis.

Experimental procedure

The data were collected during a training session at the High Performance Training Centre of Sierra Nevada. Each swimmer performed 10 start techniques in a counterbalanced order (grab start and kick-start) and 2 minutes rest in-between each trial. When performing kick-start technique, the swimmers placed their their usual rear leg on the back plate support (10 right and 6 left). After the trigger, which was audible to the swimmers and visible to each camera as a flashing light, the swimmers performed a dive followed by a 5 m glide at maximum velocity. The trial with the best performance at 5 m mark was used for the statistical analysis.

Each trial was recorded above the water by four high-definition cameras (Nikon 1 J1, frame rate 60 Hz, resolution 1280x720 and shutter speed 1/1000) were used to record each trial. The cameras were placed on both sides of the swimming pool, two on each side at 2.80 m and 10 m beyond the front edge of the starting block. One more camera (Sony HDR-AS15, frame rate 60 Hz, resolution 1280x720 and shutter speed 1/1000) was placed underwater to capture the time between the starting signal and the head passage at 5 m mark.

A control object (2 m × 1.55 m × 0.81 m) with thirty-four control points was used to calibrate the plane of motion. True coordinates were reconstructed using a 3D linear direct transformation algorithm (DLT) (Abdel-Aziz & Karara, 1971; de Jesus et al., 2015). To determine the accuracy of calibration procedure, the root mean square error (RMS) of the thirty-four control points was calculated. The accuracy of the grid coordinates was less than 0.82 mm for each of the above water cameras. For the CoM kinematics, an anthropometric model with twenty-one points based on de Leva (1996) was used. Kwon 3D XP software was used for the manual digitalization.

Data analysis

All body coordinates were processed using a Butterworth low-pass filter with a cut-off frequency of 6 Hz. The swimming starts were defined by three phases: 1) **block time** (s), time from the starting signal until the swimmers' feet leave the block; 2) **flight time** (s), time from the feet leave the block until the hands make contact with the water surface; and 3) **entry time** (s), the sum of block time plus flight time. To determine the performance of the aerial phase the **time to 5 m** (s) was calculated. It was defined as the elapsed time from the starting signal until the swimmers' heads reached the 5 m distance. This time was considered as a performance estimate for the block and flight phases, excluding underwater undulatory movement.

For a detailed biomechanical analysis of the kick-start techniques, further variables were included: **CoM at starting signal** (m), horizontal body's CoM position at the starting signal relative to the edge of the platform; **CoM at water entry** (m), horizontal body's CoM position when the swimmer's hands enter the water; **flight distance** (m), horizontal body's

CoM displacement between toe-off and when the swimmer's hands enter the water; **take-off angle** (°), angle formed by the hips and fingertips relative to a horizontal vector at instant when the feet leave the block; **entry angle** (°), angle formed by the hip and hands relative to a horizontal vector at instant when the hands make contact with the water; **initial body angle** (°), body orientation at take-off calculated by the angle formed by the legs' CoM and the body's CoM relative to the horizontal axis; **final body angle** (°), body orientation at hands entry calculated by the angle formed between the legs' CoM and the body's CoM relative to the horizontal axis; **horizontal take-off velocity** (m/s), magnitude of the horizontal velocity of the CoM vector at take-off; **hands-off horizontal acceleration** (m/s^2), magnitude of the horizontal acceleration of the CoM vector at the take-off hands instant; **take-off horizontal acceleration** (m/s^2), magnitude of the horizontal acceleration of the CoM vector at take-off; **peak of horizontal acceleration** (m/s^2), maximum magnitude of the horizontal acceleration of the CoM vector; **time of peak horizontal acceleration** (s), instant when the maximum horizontal acceleration is produced; **loss of horizontal velocity** (m/s), difference between the horizontal velocity at 5 m distance and horizontal velocity at take-off.

To understand the characteristics of rotation in the mediolateral axis during the flight phase, the following variables were analysed:

1) The **total angular momentum** (H) ($kg.m^2/s$) of the swimmer's body about the mediolateral body axis was oblock timeained following the method based on Dapena (1978).

$$H = \sum_{i} ([m_i \times M \times (v_{i1} \times v_{i2})]/\Delta t + I_i \times \omega_i) \tag{1I.1}$$

The first term $[m_i \text{ x } M \text{ x } (v_{i1} \text{ x } v_{i2})]/\Delta t$ represents the remote contribution; $I_i \text{ x } \omega_i$ represents the distal contribution; m_i is segment mass; M is the mass of the whole body; v_{i2} and v_{i2} are the location vectors of the segment in two successive frames; Δt is the interval time between two frames; I_i is the segment's moment of inertia and ω_i is the angular velocity of the segment about the total body mediolateral axis.

In order to eliminate the differences in the rotation caused by the swimmers' anthropometrical characteristics the angular momentum values ($kg.m^2/s$) were normalized by dividing them their mass (kg) and the square of their standing height (m). Furthermore, to facilitate the interpretation of the results values of normalized angular momentum (Nam) were multiplied by 10^3 as a consequence of the resulting results are rather small. In this regard the results of Nam are expressed in units $s^{-1}.10^{-3}$ (Dapena, 1980; Hinrchs, 1987; Kwon, 1996; Yeadon, 1990).

2) **Moment of inertia** ($kg.m^2$) of the swimmer's body about the mediolateral body axis was obtained by the method based on Hinrichs (1978).

3) **Rotation angle** (°) was defined as the body rotation generated during the flight phase. It was calculated as follows:

$$\text{RHx} = \text{Nam} \times \left(\frac{1}{I_x}\right) \times \text{Flight time} \tag{1I.2}$$

$$\text{Rotation angle (RHx)} = \text{Angular velocity } (\omega) \times \text{Flight time} \tag{1I.3}$$

$$\text{RHx} = \text{Nam} \times \frac{1}{\text{Momentum of inertia (Ix)}} \times \text{Flight time} \tag{1I.4}$$

Statistical analysis

Descriptive statistics were performed to calculate the mean and the standard deviation for each variable. The Shapiro Wilk test confirmed all parameters were normally distributed. Then, a paired Student's t-test was used to determine the differences between grab start and kick-start. Effect size was calculated using Cohen's d to establish the strength of the differences between each technique. The strength of the effect size was interpreted on the following scale: 0 - 0.2 trivial; 0.2 - 0.6 small; 0.6 - 1.2 moderate; 1.2 - 2.0 large; 2.0 - 4.0 very large and >4 almost perfect (Hopkins, 2002). The Pearson correlation coefficient (r) was used to establish the relationships among the aerial phase variables in kick-start. Based on Hopkins (2002), the Pearson correlation coefficient (r) was interpreted as follows: 0.0 - 0.1 trivial; 0.1 - 0.3 small, 0.3 - 0.5 moderate; 0.5 - 0.7 large; 0.7 - 0.9 very large and 0.9 - 1.0 almost perfect. The statistical analysis was carried out using SPSS v19.0 software. Statistical significance was set at $p < 0.05$.

b. Results

The kick-start presented smaller values for all temporal variables on the block and along the flight phase ($p < 0.005$). Moreover, these advantages were maintained up to 5 m distance (Table 1I.1). Smaller mean values of the flight distance, CoM at water entry and loss of horizontal velocity were observed for kick-start compared with those for grab start. Despite the difference found between kick-start and grab start for these parameters, they had a small effect size. For kick-start, large and very large differences in the horizontal acceleration were presented at the hands-off instant and maximum pike, respectively. In contrast, time of peak horizontal acceleration and take-off horizontal acceleration for kick-start showed smaller mean values than those for grab start (Table 1I.1).

Table 1I.1. Mean, standard deviation, p-value and effect size in each variable analysed for kick-start and grab start (*p <0.05).

	Kick-start	Grab start	p-value	Effect Size
Block time (s)	0.71 ± 0.08	0.88 ± 0.08	0.001*	-2.12
Flight time (s)	0.20 ± 0.04	0.22 ± 0.05	0.008*	0.44
Entry time (s)	0.91 ± 0.06	1.10 ± 0.06	0.001*	-3.16
Time to 5 m (s)	1.59 ± 0.16	1.75 ± 0.14	0.001*	-1.06
Flight distance (m)	0.85 ± 0.22	0.94 ± 0.21	0.002*	-0.41
CoM at starting signal (m)	-0.11 ± 0.06	-0.11 ± 0.07	0.837	-0.04
CoM at water entry (m)	1.76 ± 0.23	1.89 ± 0.28	0.002*	-0.50
Horizontal take-off velocity (m/s)	4.22 ± 0.33	4.18 ± 0.31	0.300	0.12
Take-off angle (°)	29.22 ± 3.27	27.84 ± 4.34	0.194	0.35
Entry angle (°)	36.98 ± 4.55	38.12 ± 5.44	0.261	-0.27
Hands-off horizontal (m/s^2)	10.66 ± 1.93	7.00 ± 1.56	0.001*	2.08
Take-off horizontal acceleration (m/s^2)	1.89 ± 0.92	3.73 ± 1.34	0.001*	1.60
Peak of horizontal acceleration (m/s^2)	12.13 ± 2.39	9.67 ± 1.62	0.001*	1.20
Time of peak horizontal acceleration (s)	0.42 ± 0.08	0.67 ± 0.11	0.001*	-2.59
Loss of horizontal velocity (m/s)	1.02 ± 0.38	1.32 ± 0.32	0.001*	-0.39
Initial Body Angle (°)	7.33 ± 4.36	-2.55 ± 4.95	0.001*	2.11
Final Body Angle (°)	29.88 ± 5.47	24.13 ± 5.17	0.001*	1.08
Nam ($s^{-1}.10^{-3}$)	106.59 ± 14.87	100.50 ± 25.54	0.374	0.29
RHx (°)	21.19 ± 4.98	25.08 ± 4.50	0.002*	-0.81
1/Ix ($kg.m^2$)	0.020 ± 0.008	0.024 ± 0.006	0.014*	-0.70

For kick-start, there was shorter rotation during the flight phase (RHx) compared to that for grab start (p = 0.017); the rotation was 3.89º ± 2.75º less for kick-start than for grab start (table 1I.1). Body rotation was dependent on Nam, 1/Ix and flight time. Therefore, the ratio of each factor was calculated to describe its contribution to the lower rotation produced during kick-start. The results showed a contribution of 70% and 30% for 1/Ix and flight time, respectively. However, Nam did not affect the loss of rotation. Moreover, significant differences were only found for 1/Ix (p = 0.014) and flight time (p = 0.008); these parameters were smaller in value for kick-start than those for grab start. In contrast, Nam showed similar results (p = 0.374) between the two start techniques. Finally, very large differences in the body angle at the toe-off instant (p < 0.001) and water entry (p = 0.005) were shown between both techniques, where kick-start presented longer values than those for grab start (Figure 1I.1). Figure 1I.1 displays the differences in the body orientation between grab start and kick-start.

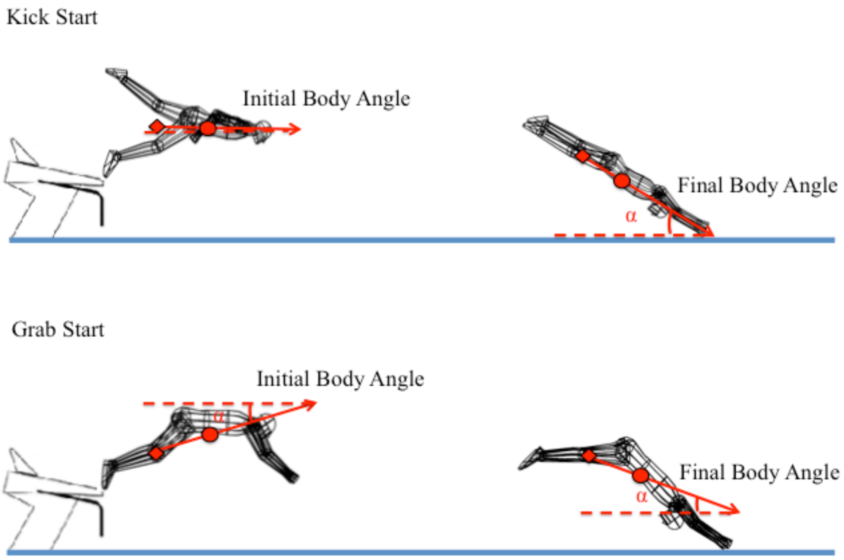

Figure 1I.1. Body orientation differences produced for the kick-start and the grab start (formed by the leg COM and body COM) following the movement direction during the take-off and entry of hands.

Table 1I.2 presents the Pearson's correlation for the aerial phase parameters during kick-start. Significant correlation was shown between block time and time of peak of horizontal acceleration, hands-off horizontal acceleration, flight time, entry time, flight distance, loss of horizontal velocity and time to 5 m. Flight time was significantly related to time of peak of horizontal acceleration, hands-off horizontal acceleration, RHx, flight distance, take-off angle and final body angle. A significant relationship between entry time, time of peak of horizontal acceleration and loss of horizontal velocity was also observed. Finally, for time to 5 m, there were positive correlations with the time of peak of horizontal acceleration and loss of horizontal velocity. In contrast, shorter time to 5 m was related to greater flight distance, CoM at water entry, hand-off horizontal acceleration, peak of horizontal acceleration and horizontal take-off velocity.

Regarding the parameters related to horizontal acceleration, significant correlation was observed between hands-off horizontal acceleration and peak of horizontal acceleration, time of peak of horizontal acceleration, CoM at water entry, flight distance and horizontal take-off velocity. Peak of horizontal acceleration presented a relationship with flight distance, CoM at water entry and horizontal take-off velocity (all $p = 0.001$). For time of peak of horizontal acceleration, a significant correlation was found with final body angle and loss of velocity. In contrast, no significant correlation between horizontal acceleration at take-off ($p > 0.005$) and the other aerial phase parameters was noticed.

Further correlations were found among the angular and spatial parameters. There was a significant correlation between flight distance, final body angle, CoM at water entry, and RHx. CoM at water entry was found to have a very large correlation with horizontal take-off velocity. Entry angle was related to horizontal take-off velocity, take-off angle and CoM at water entry. Furthermore, initial body angle was related to RHx. Finally, negative correlations were found between final body angle and loss of horizontal velocity and between final body angle and time to 5 m; however, of the relationship was not statistically significant ($r = -0.436$, $p = 0.091$ and $r = -0.461$, $p = 0.072$, respectively).

Large and very large effect sizes were shown for all the significant correlations. Only the relationships between flight time and flight distance ($r = 0.914$) and between block time and the time of peak of horizontal acceleration ($r = 0.910$) presented an almost perfect correlation. In contrast, time of peak of acceleration showed moderate relationships with time to 5 m ($r = 0.498$) and with flight distance ($r = -0.498$). Trivial ($r = 0.0 - 0.1$), small ($r = 0.1 - 0.3$) and moderate ($r = 0.3 - 0.5$) correlations were found in Nam and CoM at starting signal and the other aerial phase parameters. Furthermore, there were no significant correlations ($p > 0.05$).

Table 1I.2. Pearson's correlation values between the airborne phase parameters of the kick-start (*p < 0.05)

	Block time	Flight time	Entry time	Time to 5 m	Flight distance	CoM at water entry	Horizontal take-off velocity	Take-off angle	Hands-off horizontal acceleration	Time of peak of horizontal acceleration	Initial body angle
Flight time	-0.585*										
Entry time	0.809*	0.001									
Time to 5 m	0.563*	-0.377	0.428								
Flight distance	-0.627*	0.914*	-0.112	-0.681*							
CoM at water entry	-0.159	0.469	0.143	-0.750*	0.709*						
Horizontal take-off velocity	0.034	-0.002	0.045	-0.763*	0.351	0.812*					
Take-off angle	-0.009	0.508*	0.347	0.326	0.235	-0.035	-0.416				
Hands-off horizontal acceleration	-0.600*	0.602*	-0.300	-0.851*	0.803*	0.711*	0.595*	-0.135			
Time of peak of horizontal acceleration	0.910*	-0.453	0.801*	0.498*	-0.498*	-0.013	0.095	0.046	-0.556*		
Peak of horizontal acceleration	-0.312	0.442	-0.059	-0.772*	0.658*	0.787*	0.742*	-0.115	0.711*	-0.114	
Loss of horizontal velocity	0.579*	-0.284	0.527*	0.526*	-0.373	-0.394	-0.141	0.098	-0.420	0.535*	
Final body angle	-0.441	0.559*	-0.154	-0.461	0.618*	0.401	0.146	0.103	0.441	-0.549*	0.343
Entry angle	-0.129	0.214	-0.010	0.633*	-0.124	-0.652*	-0.868*	0.603*	-0.420	-0.100	-0.234
RHx	-0.215	0.644*	0.179	-0.248	0.589*	0.426	0.080	0.320	0.206	-0.035	-0.615*
1/Ix	0.487	-0.115	0.514*	0.273	-0.133	0.051	0.082	0.400	-0.234	0.487	-0.231

c. Discussion

A detailed biomechanical analysis of the kick-start technique was designed to determine the most relevant parameters on the block and during the flight phase with the aim to determine the elements in which swimmers and coach must stress to improve the kick-start technique. With this purpose, a comparison with the grab start technique and a Pearson's correlation was made. The results of this study agreed with a previous study (Slawinski et al., 2010) that reported horizontal acceleration on the block seemed to be the key parameter needed to develop a temporal advantage for kick-start.

The significant differences observed in hands-off horizontal acceleration, peak of horizontal acceleration and time of peak of horizontal acceleration indicated a greater and faster development of horizontal acceleration during the block phase for kick-start. For this technique, a greater production of horizontal acceleration up to the take-off hands instant allowed a greater and faster increase in the horizontal velocity at this instant (Figure 1I.2). These differences in the development of horizontal acceleration and velocity were associated with greater temporal advantages when the rear foot pushed on the back plate. Moreover, the greater production of horizontal acceleration was associated with the capacity to maintain the temporal advantages obtained at the hands-off instant up to the toe-off instant. These results were consistent with Slawinski et al. (2010), who found that the maximal acceleration occurred when the rear foot pushed on the back plate. Furthermore, Nomura et al. (2010) also reported a faster increase in acceleration for kick-start relative to track start.

The faster development of horizontal acceleration suggested that a longer block time was not required to reach greater force levels for kick-start (Slawinski et al., 2010). In this regard, shorter block time and similar horizontal take-off velocity were observed for kick-start with respect to grab start. Our results and those of Slawinski et al. (2010) agreed that explosive muscle contraction and maximum muscular force seemed to be relevant in the block phase performance for kick-start. These results supported the relationship that having greater lower limb muscle power improved start performance (Beretić, Durovic, Okicic, & Dopsaj, 2013; García-Ramos et al., 2015; Slawson, Conway, Cossor, Chakravorti, & West, 2013).

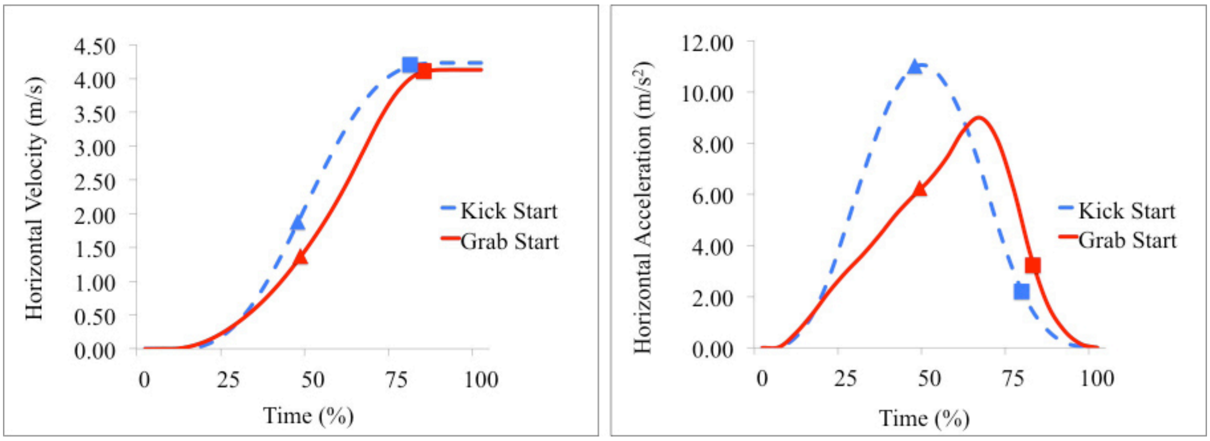

Figure 1I.2. Horizontal CoM velocity-time curve and horizontal acceleration CoM-time curve with standardized values for grab start and kick-start. Each curve was divided into two phases: take-off hands (blue triangle) and take-off (red square) for kick-start and take-off hands (red triangle) and take-off (red square) for grab start.

Differences in the ground reaction force direction relative to the CoM have been deemed the reason for greater and faster horizontal acceleration levels for kick-start during the block phase. For this technique, the results suggested that the asymmetrical leg position and back plate allowed the swimmers to develop greater force levels after the trigger because the direction of the ground reaction force vector was always placed behind the CoM (Figure 1I. 3a, b). In contrast, the parallel on-block leg position for grab start produced a resultant force direction was placed ahead of the CoM until the take-off hands instant, which caused an anticlockwise rotation that made the development of a large force difficult (Figure 1I.3a). After the take-off hands instant, the force vector, likely placed behind the CoM, permitted the production of greater force without anticlockwise rotation (Figure 1I.3b). This hypothesis was supported by previous studies that analysed force production on the block. For kick-start, Slawson, Chakravorti, Conway, Cossor, & West (2012) found positive resultant forces after the trigger (main plate 600 N and 400 N; back plate 600 N and 200 N; horizontal and vertical force, respectively) and at the take-off hands instant (more than 600 N in horizontal and vertical force). For grab start, negative resultant forces were found after the trigger (500 N and -300 N; horizontal and vertical force, respectively) and positive resultant forces after the hands-off instant (300 N in horizontal and vertical force) (Arellano, Pardillo, De La Fuente, & García, 2000).

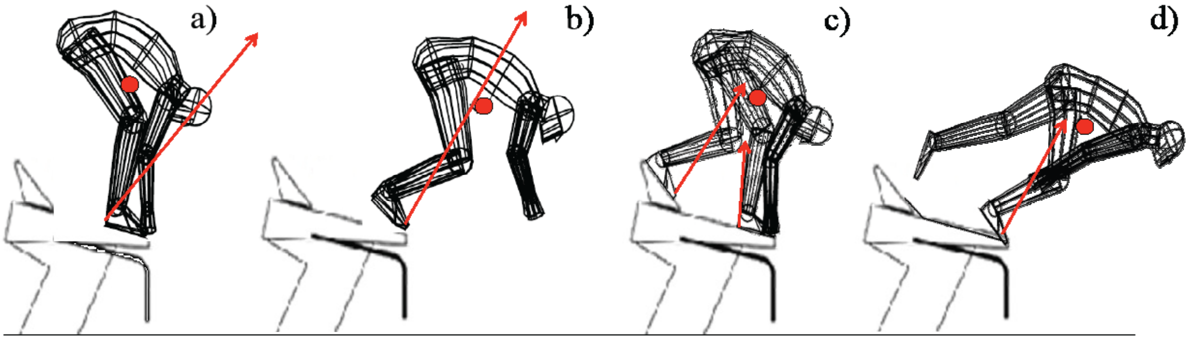

Figure 1I.3. Suggested position of ground vertical force relative to CoM for grab start (a, b) and kick-start (c, d).

Previous studies reported an association between the angular momentum at take-off and the type of water entry (McLean et al., 2000; Vantorre et al., 2010; Vantorre et al., 2011). This was because greater values of angular momentum at take-off and longer flight time were shown to permit greater body rotation during the flight phase and, consequently, greater entry angles. The present study results showed that kick-start and grab start produced similar entry angle and Nam at take-off. However, as a consequence of shorter flight time and higher momentum of inertia (smaller 1/Ix values) for kick-start, RHx was significantly smaller during the flight phase than those for grab start. As a consequence, the advantages observed in the initial body angle for kick-start (9.88º) were reduced at hands entry (5.75º). Despite smaller RHx, kick-start showed lower loss of velocity, which indicated a more effective entry into the water than for grab start. A previous study suggested that a hyperextended back at hands entry was necessary to prepare a powerful dolphin kick during the immersion phase (Fischer & Kibele, 2014). The results of this study agreed that the best entry into the water for kick-start was associated with a larger final body angle, i.e., a higher position of the lower limbs relative to the trunk.

For kick-start, the Pearson correlation coefficient results indicated that the largest final body angles were dependent on longer flight phases. Similar results were found for RHx, which showed a positive correlation with the flight time and flight distance and a negative correlation with the initial body angle. A greater displacement of the rear leg on the block encouraged a higher lower limb position relative to the trunk at the toe-off instant (Vantorre et al., 2011), which meant a greater initial body angle or a downward take-off position (Figure 1I.1). These results seemed to indicate that a smaller rear leg displacement on the block was required to obtain a greater RHx and a longer flight phase, which allowed for a greater final body angle. However, it is important to note that greater RHx and higher loss of velocity at water entry were found for grab start. These findings might support the idea that a rear leg displacement on the block that was too large would reduce the flight time and, consequently, would also reduce the body rotation during the flight phase and the final body angle. However, lower limb displacement on the block that was too small would prevent lower limb movement during the flight phase and also produce a smaller final body angle. Thus, an optimal balance between the displacement of the rear leg on the block and longer flight phase was required to obtain an optimal water entry.

This was the first study that reported the relationships among the aerial phase parameters for kick-start. The Pearson correlation coefficient indicates that the quick development of greater horizontal acceleration on the block could be the most relevant parameter to obtain the best aerial phase performance in kick-start. Significant correlation was found between hands-off horizontal acceleration, pike of horizontal acceleration, time pike of horizontal acceleration and time to 5 m (Figure 1I.4). Furthermore, horizontal acceleration was significantly correlated with all the parameters involved in the best aerial phase performance (block time, flight distance, CoM at water entry, horizontal take-off velocity, and loss of horizontal velocity). These results agreed with another study that found a large correlation between average horizontal acceleration and time to 5 m in track start; thus, average horizontal acceleration was one of the most relevant to predict the best performance at 5 m (García-Ramos et al., 2015).

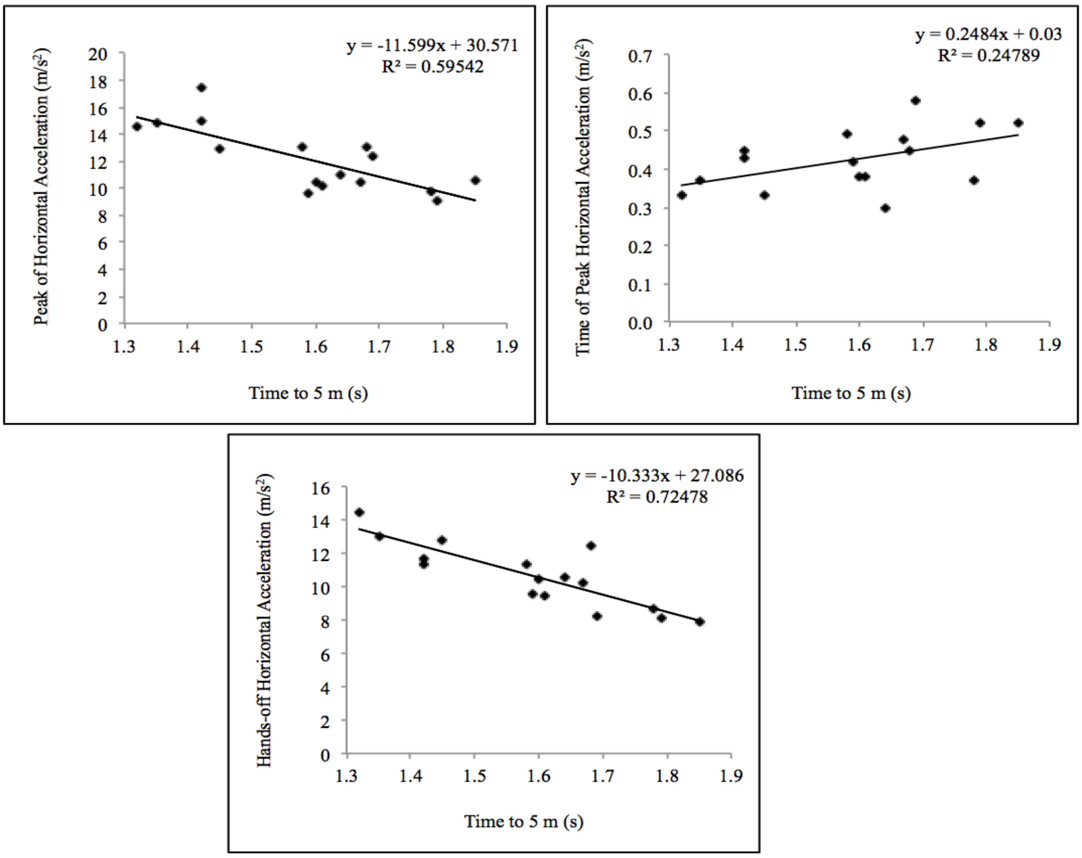

Figure 4. Linear regression of the peak horizontal acceleration, time of peak horizontal acceleration and hands-off horizontal acceleration with respect to the time to 5 m for the kick-start.

The horizontal acceleration on the block was also associated with the best block phase performance. Contrary to previous studies that used older start techniques (Fischer & Kibele, 2016; Welcher, Richard, Hinrichs, & George, 2008), no significant correlation between block time and horizontal take-off velocity was observed in our results. Our results suggested that the back plate effect allowed shorter block time with no effect on horizontal take-off velocity (Honda, Sinclair, Mason, & Pease, 2010). Greater horizontal take-off velocity values were positively correlated with peak of horizontal acceleration, hands-off horizontal acceleration and CoM at water entry. Typically, block time would be affected by this relationship because greater travel distances and larger horizontal velocities require larger horizontal force amplitudes over time (Benjanuvatra, Edmunds, & Blanksby, 2007; Vantorre, Seifert, Fernandes, VilasBoas, & Chollet, 2010b). However, Pearson's correlation related a shorter block time to a greater and faster development of horizontal acceleration, which reinforced that kick-start developed greater horizontal force in a short amount of time (Slawinski et al., 2010). These results agreed with Slawinski et al. (2010), who emphasized the relevance of the explosive muscle strength in kick-start.

Horizontal take-off velocity, take-off angle and CoM at water entry showed a large and very large significant correlation to entry angle. Furthermore, smaller entry angle was related to shorter time to 5 m. These results suggested that a shallower entry led to a quicker entry into the water (Vantorre, Chollet, & Seifert, 2014). However, entry angles that were too small can be negative if the swimmers did not reach an optimal depth during the glide phase, inducing an increase in the resistance. Consequently, further study about the optimal entry position, including the overall start performance (time to 15 m), is required.

Finally, it is important to note that a longer flight phase was also related to greater and faster development of horizontal acceleration, greater take-off angle and shorter time to 5 m. In this regard, an optimal take-off angle that permitted a longer flight phase and a shorter entry angle seemed to be relevant in the best aerial phase performance.

1.II. Analysis of the mechanics of rotation on swimming start performance

The aim of this study was to analyse the mechanics of rotation for kick-start and grab start along the aerial phase to understand the angular momentum contribution in the body rotation and the differences between symmetrical and asymmetrical techniques. With this purpose, nine elite swimmers performed the starts on the OMEGA OSB11 starting block followed by 5 m gliding at maximum velocity. Eighteen comparisons of kinematics variables across start technique were performed with critical alpha adjusted using a Holm's correction to maintain an experiment-wise type I error rate of $p < 0.05$. The differences were statistically evaluated by T-test and Wilcoxon test. Significant advantages for the kick-start were observed in all temporal variables (except in the flight time) and in the vertical take-off velocity. Similarities in the centre of mass angular momentum at take-off (120.89 ± 17.66, 126.61 ± 13.51 $s^{-1}.10^{-3}$, p-value <0.294; kick-start and grab start) caused that kick-start did not increase the temporal advantages obtained on the block at 5 m distance. In spite of the similar values of angular momentum at take-off, two different rotational movements were found for both techniques. A displacement of the rear leg and front leg on the block and during the flight respectively permits a higher lower limbs position relative to the trunk at hands entry for kick-start. However, larger rotational movement of the trunk characterized grab start.

a. Methodology

Participants

Nine elite swimmers from the Spanish National Team (5 males and 4 females) participated in this study (body mass 70.0 ± 7.7 kg; height 178 ± 9.4 cm; age 24.5 ± 5.3 years). FINA Points Score was calculated to quantify the competitive level of the swimmers. Based on the best time of the main event, a point score was ascribed to each swimmer. The FINA Points of the study sample were 824 ± 119 points. The participants signed an informed consent and the University Ethics Committee approved the procedures used for this analysis.

Experimental procedure

The data were collected during a training session at the High Performance Training Centre of Sierra Nevada. Each swimmer performed 10 starts in a counterbalanced order (grab start and kick-start) and 2 minutes rest in-between each trial from a starting block (OMEGA OSB11). The swimmers preferred the kick-start starting technique. However, in previous years they competed and trained with grab start, what means everyone has a remarkable experience with both techniques. When performing kick-start, the swimmers placed their usual rear leg on the back plate support (6 right and 3 left). After the trigger sound, audible to the swimmers and visible to each camera with a flashing light, the swimmers performed a dive followed by a glide to discard the effect of possible differences in the profiles of water entry. The trial with the best performance at 5 m was included in the analysis. Each trial was recorded above the water by four High Definition Cameras Nikon 1 J1 (frame rate 60 Hz, resolution 1280x720 and shutter speed 1/1000) placed on both sides of the swimming pool, two on each side at 2.80 m and 10 m from the edge of the pool. One additional camera (Sony HDR-AS15) was placed underwater to get the time to 5 m, with the same recording setup as the above water ones.

A control object (2 m x 1.55 m x 0.81 m) was used to calibrate the plane of motion. This structure, consisting in twelve aluminium rods and thirty-four control points, was placed on the water surface using a system of ropes. The real coordinates were reconstructed using a linear direct transformation algorithm (DLT) (3D DLT; Kwon 3D XP, 1996). To determine the accuracy of calibration procedure, the root mean square error (RMS) of the thirty-four control points was calculated. A mean calibration error of 0.78 mm was obtained. Twenty-one points were manually digitalized to define the body model of 14 segments proposed by de Leva (1996). The Kwon 3D XP software was used for the digitalization and the subsequent kinematical analysis. All of the data were processed using a Butterworth Low-pass filter with a cut-off frequency of 6 Hz.

Data analysis

Temporal, angular and kinematic variables, including velocities and angular momentum, were analysed in this study. The temporal variables were defined as follow: **block time** (s), time from the starting signal until the swimmers' feet leave the block; **flight time** (s), time from the feet leave the block until the hands make contact with the water surface; **entry time** (s), the sum of block time plus flight time; **time to 5 m** (s), elapsed time from the starting signal until the swimmers' heads reached the 5 m distance. The angular and kinematic variables included in this study were: **take-off angle** (°), angle between the horizontal axis and the velocity vector at take-off; **trunk-front leg** (°), angle between hip, shoulder and knee at take-off and entry hands; **trunk-rear leg** (°), angle between hip, shoulder and knee at take-off and entry hands. These last angles were calculated for the front leg for the kick-start and for the grab start were measured as the average between the right and left leg. **Horizontal CoM velocity** (m/s), magnitude of the horizontal velocity of the CoM vector at take-off; **vertical CoM velocity** (m/s), magnitude of the vertical velocity of the CoM vector at take-off

Mean curves of angular momentum versus time were represented for each segment CoM and for the whole body CoM. The timeline was normalized to 100% of the block time plus flight time (aerial phase) for each swimmer and each swim starting technique.

The whole body centre of mass angular momentum in the mediolateral axis was calculated as the sum of the angular momentum of each segment (Kwon, 1996):

$$H = \sum_{i} (m_i r_i \times v_i + I_{CM} \times \omega) \tag{1II.1}$$

Where the first term $\mathbf{m_i r_i \times v_i}$ is the angular momentum due to the translation of the CoM and where $\mathbf{m_i}$ = the mass of each segment; $\mathbf{r_i}$ = the position of the each segment and $\mathbf{v_i}$ = the velocity of each segment. The second term $\mathbf{I_{CM} \times \omega}$ belongs to the angular momentum due to the rotation of the body about its CoM; here $\mathbf{I_{CM}}$ is the momentum of inertia of the segment and $\boldsymbol{\omega}$ = the angular velocity of the segment.

In order to eliminate the differences in the rotation caused by the swimmers' anthropometrical characteristics the angular momentum values (kg.m^2/s) were normalized by dividing them their mass (kg) and the square of their standing height (m). Furthermore, to facilitate the interpretation of the results values of normalized angular momentum (Nam) were multiplied by 10^3 as a consequence of the resulting results are rather small. In this regard the results of Nam are expressed in units s^{-1}.10^{-3} (Dapena, 1980; Hinrichs, 1987; Kwon, 1996; Yeadon, 1990).

The angular momentum was calculated for the whole body CoM (Nam$_{CoM}$), trunk (Nam$_{trunk}$) and upper limbs (Nam$_{upper}$) in both starting techniques. In addition, the angular momentum of the rear leg (Nam$_{rear}$) and front leg (Nam$_{front}$) was calculated for the kick-start, while the right leg angular momentum (Nam_{right}) and the left leg (Nam_{left}) were also analysed for the grab start. Mean curves of Nam versus time were represented for the whole body CoM (Figure 1II.1) and for each segment CoM (Figure 1II.2). The timeline was normalized to 100% of the block time plus flight time (aerial phase) for each swimmer and each swim starting technique. Moreover, the mean values of Nam at feet take-off for each technique are presented (table 1II.1). Based on the right-handed rule positive values of Nam indicated a clockwise rotation while a counterclockwise rotation was produced with negative values.

Statistical analysis

Descriptive statistics were performed to calculate the mean and the standard deviation for each variable. After checking the data normality through the Shapiro-Wilk test, a paired t-test was applied to the variables that yielded a $p < 0.05$ in order to determine the differences between the grab start and kick-start. The Wilcoxon test was applied to variables that were not normally distributed. Since multiple comparisons are made and in order to avoid incorrectly rejecting the null hypothesis, the significance level was adjusted using the Holm's correction such as the experiment-wise type I error rate was held to $p < 0.05$ by progressively adjusting the critical p-values of each test (Lundbrook, 1998). Effect size was calculated using Cohen's (d) to establish the strength of the differences between each technique. The scale to interpret the strength of the effect size was: 0-0.2 trivial; 0.2-0.6 small; 0.6-1.2 moderate; 1.2-2.0 large; 2.0-4.0 very large and >4 almost perfect (Hopkins, 2002). The statistical analysis was performed with the statistical software SPSS v.19.0.

b. Results and discussion

With the purpose to analyse the mechanics of rotation in the aerial phase for the kick-start technique a comparison of normalized angular momentum about the mediolateral axis for the CoM and for each body segment regarding the grab start was made.

Contrarily to our expectations and to early studies that reported lower angular momentum in grab start ($H = 16.36 \pm 2.89$ kg.m^2/s) in comparison with track start ($H = 18.76 \pm 2.26$ kg.m^2/s) at take-off (Vantorre et al. 2011), the results of the present study showed similar Nam for kick-start and grab start at take-off (table 1II.1). Nam at take-off was shown determinant on the type of entry into the water such as larger Nam produced larger entry angles (McLean et al., 2000; Vantorre et al., 2010; Vantorre et al., 2011). Based on this previous literature, the results of this study suggested that similar entry into the water performance was obtained in both techniques. Consequently, the significant larger temporal advantages obtained on the block for kick-start (0.17 s less in the block time for kick start than for grab start) remained up to entry time and the time to 5 (0.15 s less at 5 m distance for kick start than for grab start) ($p < 0.001$) (table 1II.1).

Similarities in Nam at take-off were associated with the torque developed on the block and the block time. Strictly, the torque produced against the block and time of application of this torque determines the amount of Nam on the block. For grab start, longer block time implied a longer time of application of torque while the shorter block time for kick-start implied that the swimmers had to apply larger torque to obtain similar Nam than grab start. These differences were confirmed qualitatively by the mean curves observed in both techniques. A decrease of Nam before the hands take-off implied negatives values when hands let the platform for grab start. These results indicated a counterclockwise rotation of the body in this moment as a consequence of negative values of torque obtained in this moment. Afterwards an abrupt increase of Nam and longer time of application of torque produced that grab start was able to obtain similar Nam at take-off than kick-start (Figure 1II.1). In contrast, positive Nam along all block phase was observed for kick-start, however the shorter block time limited a larger increase of Nam.

Table 1II.1. Means, standard deviations and effect size obtained in the temporal, kinematic, angular variables and in the angular momentum for each body segment and the whole body at take-off between grab start and kick-start (*p < 0.05; †Wilcoxon test).

	Kick-start	**Grab start**	**p-value**	**Effect Size**
Block time (s)	0.66 ± 0.06	0.83 ± 0.07	0.001*	-2.60
Flight time (s)	0.22 ± 0.05	0.24 ± 0.05	0.056	-0.39
Entry time (s)	0.89 ± 0.06	1.07 ± 0.06	0.001*	-3.00
Time to 5 m (s)	1.56 ± 0.15	1.71 ± 0.13	0.001*	-1.06
Take-off angle (°)†	-13.7 ± 5.2	-9.9 ± 4.9	0.009	-0.74
Trunk-front leg$_{\text{take-off}}$ (°)	139.9 ± 7.9	139.7 ± 11.7	0.930	0.02
Trunk-front leg$_{\text{entry}}$ (°)	165.2 ± 10.2	154.2 ± 23.6	0.116	0.60
Trunk-rear leg$_{\text{take-off}}$ (°)	172.2 ± 8.6	139.7 ± 11.7	0.001*	3.16
Trunk-rear leg$_{\text{entry}}$ (°)	175.32 ± 11.2	154.2 ± 23.6	0.015	1.14
Vertical take-off velocity (m/s)	-1.99 ± 0.20	-1.77 ± 0.09	0.004*	-1.41
Horizontal take-off velocity (m/s)	4.12 ± 0.31	4.05 ± 0.21	0.185	0.26
Nam ($s^{-1}.10^{-3}$)	120.89 ± 17.66	126.61 ± 13.51	0.294	-0.36
Nam$_{\text{trunk}}$ ($s^{-1}.10^{-3}$)	8.93 ± 3.30	11.63 ± 1.80	0.001*	-1.01
Nam$_{\text{upper limbs}}$ ($s^{-1}.10^{-3}$)	16.40 ± 11.76	15.78 ± 5.91	0.811	0.06
Nam$_{\text{right-front leg}}$ ($s^{-1}.10^{-3}$)	50.10 ± 4.84	40.92 ± 7.78	0.008	1.41
Nam$_{\text{right-rear leg}}$ ($s^{-1}.10^{-3}$)	33.85 ± 14.11	40.92 ± 7.78	0.194	-0.62
Nam$_{\text{left-front leg}}$ ($s^{-1}.10^{-3}$)	50.10 ± 4.84	38.46 ± 7.34	0.001*	1.87
Nam$_{\text{left-rear leg}}$ ($s^{-1}.10^{-3}$)	33.85 ± 14.11	38.46 ± 7.34	0.407	-0.40

In spite of the similarity in Nam at take-off, important differences in the body segments movement along the flight phase was observed between the both techniques, which let two different body positions at hands entry instant.

Significant larger values were found in Nam_{front} than Nam_{left} at take-off ($p < 0.001$; effect size = 1.87). Larger effect size was also shown in Namright-front leg however, significant differences were slightly missed ($p = 0.008$; effect size = 1.41) (table 1II.1). A further study with larger samples may be able to establish this variable as a likely difference between kick start and grab start. The differences between the front leg and lower limbs in grab start indicated that front leg in kick-start moved more during the flight phase.

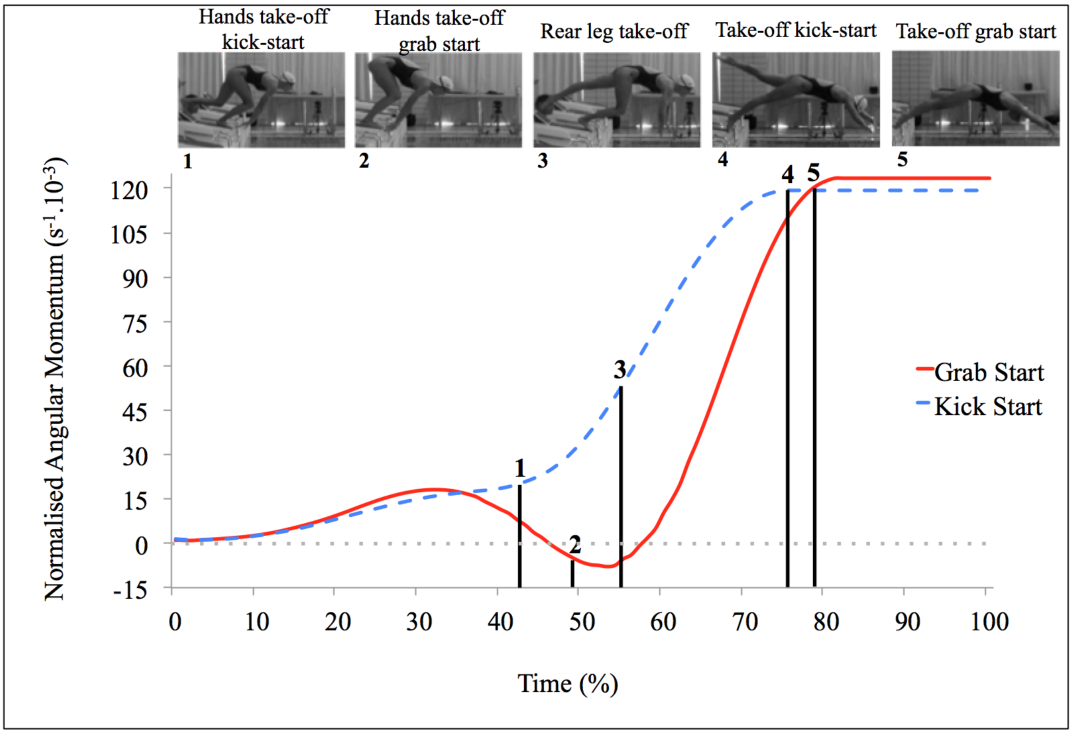

Figure 1II.1. Differences in the whole body CoM angular momentum for grab start and kick-start with standardized values.

The mean curves of lower limbs (Figure 1II.2) showed similar profiles in Nam_{right} and Nam_{left} for grab start and Nam_{front} for kick-start. Moreover, these segments obtained the peak values of Nam after the take-off. In contrast, the rear leg in the kick-start achieved the maximum value prior to take-off and after the rear foot left the block. These results suggest that the asymmetrical position on the block as well as the rear foot back plate support allowed swimmers to produce an upward displacement during the block phase with the rear leg. This upward displacement of the rear leg on the block produced a higher position at take-off than the front leg as well as a more forward and downward direction than grab start. This take-off position is also supported by the significant differences found in the vertical take-off velocity, with larger negative values for kick-start. In agreement with previous studies (Benjanuvatra, Lyttle, Blanksby, & Larkin, 2004; Vantorre et al., 2011) an asymmetrical position on the block produces higher horizontal impulse while higher vertical impulse is produced with symmetrical positions. These results were associated with an upward movement of the rear foot during the block phase, which leads to a more downward body position at take-off.

As a consequence of the higher position for the rear leg that for the front leg at take-off, during the flight the front leg made an upward movement toward the rear leg with the objective of entering the water with both legs together, as shown by the increase of Nam_{front} after take-off (Figure 1II.2). As a consequence swimmers was able to reach the water with a higher upper limbs position relative to the trunk than during grab start.

In contrast, the symmetrical starting position of grab start does not permit a displacement of the lower limbs prior to take-off; consequently the body rotation is lower with a more horizontal body position at take-off. Moreover, the take-off with both legs together make the lower limbs displacement difficult during the flight phase so that they showed constant values of Nam_{right} and Nam_{left} during the flight phase (Figure 1II.2). In this technique, larger rotation of the trunk seems to be the key of an optimal water entry. Significant larger values in Nam_{trunk} at take-off for grab start indicated a higher rotation of this segment along the flight phase than in kick-start ($p < 0.001$; effect size = -1.01). It is suggested that due to the absence of the movement for the lower limbs on the block as well as the limited rotation of these segments in the flight phase, swimmers produce a slightly higher Nam_{trunk} in grab start to entry into the water in a more hydrodynamic position.

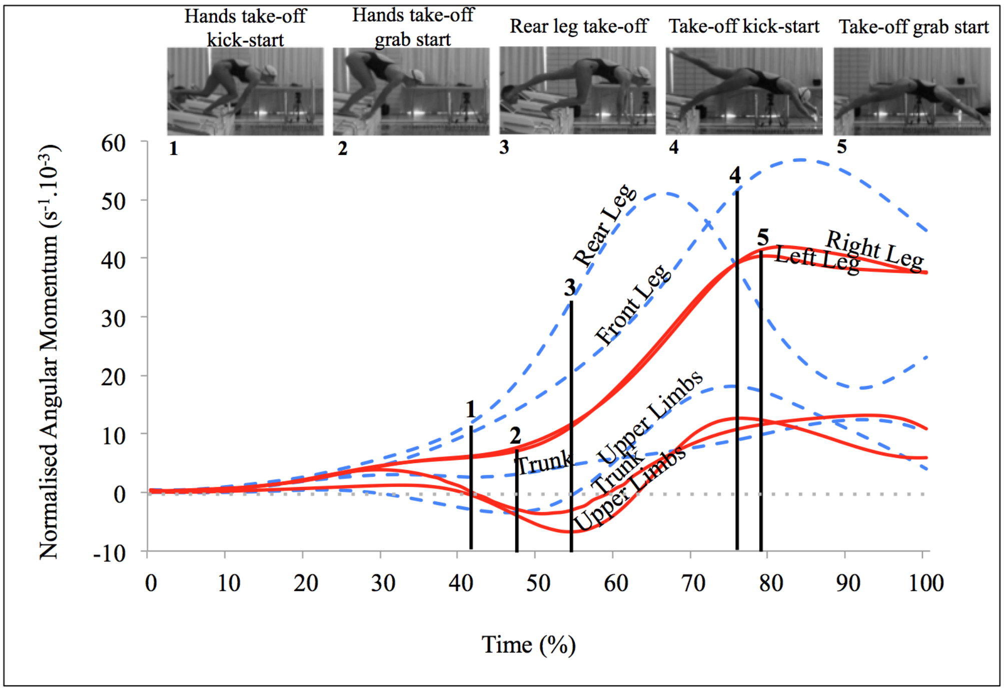

Figure 1II.2. Differences in angular momentum of each body segment for grab start and kick-start with standardized values (blue lines correspond to kick-start and red lines correspond to grab start).

The lower limbs rotational movements on the block and during the flight phase were also supported quantitatively by the differences obtained in the angular variation from the take-off to the water entry. Differences of 32.2° between trunk-front legtakeoff (139.9 ± 7.8°) and trunk-rear leg$_{\text{take-off}}$ (172.1 ± 8.5°) for kick-start indicated a rear leg upwards movement during the block phase. With the objective to perform a water entry with both legs together, swimmers, consequently, drove the front leg towards the rear leg during the flight phase. While the front leg produced a movement of 25.2° at flight (trunk-front leg$_{\text{entry}}$ - trunk-front leg$_{\text{take-off}}$) the rear leg only changed 3.1° (trunk-rear leg$_{\text{entry}}$ - trunk-rear leg$_{\text{take-off}}$). In the case of grab start both legs leave the starting block together, as consequence of this symmetrical position lower limbs showed a lower position (trunk-front leg$_{\text{take-off}}$; 139.6 ± 11.7°) relative to the rear leg for kick-start at take-off (trunk-rear leg$_{\text{take-off}}$; 172.1 ± 8.5°). During the flight phase the range of motion of the lower limbs was smaller for grab start (trunk-front leg$_{\text{entry}}$ - trunk-front leg$_{\text{take-off}}$ = 14.5°) when comparing with kick-start (25.2°). These results suggest a higher lower limbs position relative to the trunk at hands entry for kick-start.

CONCLUSIONS

The main advantage for kick-start over the grab start was associated with the faster development of higher horizontal acceleration on the block. The maximum horizontal acceleration is obtained before the rear foot left the back plate. Consequently, similar horizontal take-off velocity and angular momentum at take-off with significantly shorter block time is obtained with the kick-start than with the grab start. In spite of the similar amount of angular momentum at take-off, the kick-start showed lower body rotation during the flight phase. The upward displacement of the rear leg during the block phase leads to a more downward body position at take-off than for grab start. Consequently, the flight phase is reduced limiting the body rotation. During the flight phase, different rotational movements are developed by the kick-start and grab start. An upward displacement of the front leg towards the rear leg characterized the body rotation for kick-start. In contrast, grab start is characterized by a downward displacement of the trunk during the flight phase. As a consequence of the body position at take-off and in spite of the smaller body rotation during the flight, kick-start leads a higher lower limbs position relative to the trunk at water entry.

An increasing in the body rotation and therefore an increasing in the lower limbs displacement during the flight phase for kick-start improves the water entry. Both factors allow to swimmers reach the water with a higher lower limbs position relative to the trunk reducing the loss of horizontal velocity and the time to 5 m. Our date demonstrated that with the objective to increase the lower limbs displacement, swimmers must limit the rear leg displacement on the block and increase the take-off angle and the flight phase.

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Development of angular momentum about the mediolateral body axis during the kick-start technique

CHAPTER 2

The results included in this chapter belong to studies carried out in the Institute of Sports and Sport Science at the University of Kassel, Germany, under the supervision of Prof. Armin Kibele and in collaboration with Dr. Sebastian Fischer and Nils Eckardt.

INTRODUCTION

The total swim start performance is assessed at the time between the starting signal and when the swimmer reaches the 15-m. Based on this criterion, three swim start phases are roughly distinguished (Guimaraes & Hay, 1985): the block phase (the time interval between the starting signal and the take-off), the flight phase (the time between the take-off and the hands get the water), and the water phase (defined as the time spent between the moment when hands make contact with the water and the beginning of the swimming movement). The water phase was identified as the most relevant phase to obtain the best swim start performance (Fischer & Kibele, in press; Guimaraes & Hay, 1985). In order to obtain an optimal water phase performance, the main purpose for a swimmer is to maintain the velocities created on the block and flight phase as long as possible (Elipot, Dietrich, Heilard, & Houel, 2010; Elipot et al., 2009; Houel, Elipot, André, & Hellard, 2013; Houel, Elipot, Andrée, & Hellard, 2010; Tor, Pease, & Ball, 2014, 2015a). With this objective, to minimize the hydrodynamic resistance (drag force) at water entry and the glide phase is essential (Tor et al., 2014).

The water entry was described as the first relevant factor to obtain an optimal start performance (Mason, Alcock, & Fowlie, 2007). An optimal body position at hands entry and diving depth appear to be crucial features for reducing hydrodynamic resistance and body deceleration following water contact (Cossor, Slawson, Shillabeer, Conway, & West, 2011; Fischer & Kibele, 2016; Tor et al., 2014; Tor, Pease, & Ball, 2015b). Recently, Fischer and Kibele (2010) after the examination of the kinematic differences relative to the entry behaviour of sixteen male elite swimmers in the kick-start technique found a significant and strong relationship between the hip angle at the first contact with the water and the starting performance (measured by the time to 7.5 m) (r = -0.72). Larger hip angle at water entry was suggested to minimize the loss in horizontal velocity due to the use of a dolphin-kick after the feet immersion, lead to an optimal dive depth and consequently shorter times to 7.5 m.

In swimming starts, the amount of angular impulse produced during the block phase has been shown a determinant factor on the water entry. This factor determines the body rotation performance during the flight phase and thus the body position at hands entry (Vantorre et al., 2010; Vantorre et al., 2011). Larger angular momentum values at take-off will permit to swimmers larger rotational movements of the lower limbs in the transverse axis during the flight and greater entry angles (Vantorre et al., 2010). Vantorre et al. (2010) after the analysis of the different start styles with a the grab start position on the block found angular momentum values at take-off of 14.7 ± 2.92 kg.m2/s for the “flat start”, i.e. with a more horizontal body orientation at hands entry (entry angle: 23.4 ± 2.2°). In contrast, for the “pike start” i.e., with a more vertical body orientation at hands entry and “Volkov start” (characterized by an arm swing during the flight phase) larger angular momentum values at take-off (18.0 ± 0.6 kg.m^2/s and 17.5 ± 0.4 kg.m^2/s respectively) and larger entry angle (24.6 ± 4.8° and 28.2 ± 2.5° respectively) were detected. In this regard, a higher angular momentum on the block and the manipulation of the body segments to control the sagittal plane moment of inertia of the body and angular velocity during the flight phase are two important factors of swimmers’ start performance.

The angular momentum is a commonly parameter used in sports like diving skills, gymnasts and jumping skills in track and field. However, few studies are available presenting angular momentum data in swim starts (McLean, Holthe, Vint, Beckett, & Hinrichs, 2000; Vantorre et al., 2010; Vantorre et al., 2011). Moreover, a previous study about somersaulting diving showed that the body continues rotating in the direction of the somersaults after the hands make contact with the water (Miller, 2000) but none evaluation about the body rotation produced at water entry was made.

As a consequence of the absence of studies including an analysis of the angular momentum during the swim start, two different studies were carried out providing a detailed analysis of angular momentum developed from the starting signal to the gliding phase during the kick-start.

The first study was focused on the evaluation of the different strategies of the development of angular momentum on the block for the kick-start. Moreover, an analysis of the factors involved in the angular momentum production and the effect on the different temporal and kinematic variables involved on the kick-start performance was included. With this purpose thirty-six elite swimmers were analysed by a cinematographic method using a 2D DLT data collection and a manual tracking. The second study was focused on the qualitative evaluation of the development of angular momentum from the block to the glide phase. With this purpose, different strategies of angular momentum relative to the speed and the body angles adopted were described. For that study six elite swimmers and a total of twelve kick-start techniques were analysed. The numerical results were exported by a cinematographic method using a 3D DLT data collection for the block and flight phase and a 2D data collection for the water phase with automatic tracking. To our knowledge, both studies are the first that offers a complete analysis of the angular momentum in the swimming starts.

2.I. Take-off strategies of angular momentum during the kick-start technique

The angular momentum developed on the block is a parameter with a great relevance over the water entry in swimming starts. This parameter was analysed in older techniques such as the grab start and track start; however, there are a lack of studies including this parameter during the kick-start. The purpose of this study was to analyse the time-course of the normalized angular momentum about the mediolateral body axis on the block during the kick-start to identify different take-off strategies. Moreover, an analysis of the effects of angular momentum on the block on the performance in the different phases of the kick-start technique was made. With this purpose we analyse the block phase during the kick-start in thirty-six elite swimmers (24 males and 12 females). As we expected, the results of the cluster analysis showed four different strategies for normalized angular momentum. The main differences between the normalized angular momentum strategies were found in the front knee angle at starting position and in the arm displacement along the block phase. The largest values of front knee angle and a proximal positioning of the arms relative to the trunk with little movement were related with larger normalized angular momentum values at take-off. In addition, shorter block time, entry time and time to 5 m were associated with larger normalised angular momentum values at take-off.

a. Methodology

Participants

To carry out the objectives purposed in this study, thirty-six elite swimmers (1.82 ± 0.09 m, 76.89 ± 10.23 kg, 25.03 ± 3.07 years, 685 ± 140 FINA points for the 100-m freestyle event) from the Spanish National Team and the German National Team volunteered to participate in this study. The total sample included 24 male (1.87 ± 0.06 m, 81.83 ± 6.99 kg, 24.71 ± 2.83 years) and 12 female (1.72 ± 0.05 m, 67.00 ± 8.42 kg, 25.67 ± 3.55 years). The participants signed an informed consent and the University Ethics Committee approved the procedures used for this analysis.

Experimental procedure

Two different testing sessions (one each for the Spanish and German National Teams) were conducted to obtain video footage of the kick-start with the swimmers' preferred starting posture. In previous years the swimmers competed and trained with kick-start, what means everyone has a remarkable experience with this technique. Prior to each testing, individual warm-up programmes were performed. For all of the testing trials, the swimmers were instructed to perform two starts with maximal effort to 15 m beyond the starting block. The swim starts were initiated by an acoustic signal linked to a flashlight to allow them to be captured on video. The trial with the shortest time to 5 m was used for the statistical data analysis. In this respect, the time to 5 m was considered to represent a performance estimate for the block phase and the flight phase that excluded underwater undulatory movement.

For each testing session two different procedures were used for the data collection. For the Spanish National Team's testing session one overwater camera (Nikon 1 J1) and one underwater camera (Sony HDR-AS15) were used to record each start trial (frame rate of 60 Hz). Both cameras were positioned perpendicular to the plane of motion on the left side of the swimming pool, at 2.80 m and 5 m from the front edge of the block to capture the swimmer's behaviour on the block and the instant when the swimmers' head crossed the 5 m mark, respectively. To calibrate the plane of motion on the block, a 2D structure (2 m x 1.55 m) with eighteen control points was used. For the German National Team's testing session, one overwater camera and one underwater camera (Sony DCR-TRV900E Pal recording at 50 Hz) were positioned perpendicular to the plane of motion on the right side of the pool at 0 m and 5 m, respectively, beyond the block to capture the swimmer's behaviour on the block and the instant when the swimmer's head crossed the 5 m mark. A 2D structure (2 m x 2 m) with thirty-eight control points was used to calibrate the plane of motion on the block.

For the centre of mass (CoM) kinematics, the following anatomical points were identified to calculate the body model based on de Leva (1996): vertex, centre of the ear, cervical, shoulder, elbow, wrist, fingertip, hip, knee, ankle, heel and finger toe. The manual digitalisation of all anatomical points, reconstruction, filtering and further kinematic analysis were performed using the Kwon 3D XP software. True coordinates were reconstructed using the direct linear transformation algorithm (DLT) (Abdel-Aziz, & Karara, 2000; de Jesus et al., 2015; Kwon, & Casebolt, 2010). To determine the accuracy of calibration procedure, the root mean square error (RMS) of the thirty-four control points was calculated The accuracy of the calibration procedure was less than 0.78 cm and 0.52 cm for the overwater cameras used in the Spanish and German National Team's testing session, respectively. In order to ensure the reliability of the data, the digitalisation process was performed twice by two different researches. Test-retest using Pearson's correlation was calculated for each coordinate value. Coefficient correlation (r) results ranged from 0.73 to 0.99 for each coordinate value of the segmental points, which represents high reliability of the digitisation process (Hopkins, 2000).

Data analysis

All body coordinates were processed using a Butterworth low-pass filter with a cut-off frequency of 6 Hz. The following variables were selected for analysis: **Time to hands-off** (s); time between the starting signal and the hands leaves the block; **block time** (s); time from the starting signal until the swimmer leaves the starting block; **flight time** (s), time between the swimmer leaves the block and the hands make contact with the water; **entry time** (s), sum of block time and flight time; **time to 5 m** (s), time elapsed between the starting signal and the swimmer's head passing 5 m; **horizontal CoM velocity** (m/s), magnitude of the horizontal velocity of the CoM vector at take-off; **vertical CoM velocity** (m/s), magnitude of the vertical velocity of the CoM vector at take-off; **entry distance** (m), horizontal displacement of the CoM between the starting signal and the hands make contact with the water; **take-off angle** (°), angle between the horizontal axis, toe and hip for the front leg at take-off; **shoulder angle** (°), angle between the hip, shoulder and elbow; **front hip angle** (°), angle between the hip, shoulder and knee for the front leg; **rear hip angle** (°), angle between the hip, shoulder and knee for the rear leg; **front knee angle** (°), angle between the hip, knee and ankle for the front leg; **rear knee angle** (°), angle between the hip, knee and ankle for the rear leg.

The **total angular momentum** (H) of the swimmer's body about the mediolateral body axis was obtained by adding the angular momenta of all the segments into which the body was divided according to the CoM model (Kwon, 1996).

$$H = \sum_i (m_i r_i \times v_i + I_{CM} \times \omega) \qquad (2I.1)$$

For the segment angular momenta, $m_i \cdot r_i \cdot v_i$ represents the remote contribution and $I_{CM} \cdot \omega$ represents the distal contribution, with m_i = segment mass, r_i = the segment centre of mass distance from the total body centre of mass, v_i = the angular velocity of the segment about the segment mediolateral axis, I_{CM} = the segment's moment of inertia, and ω = the angular velocity of the segment about the total body mediolateral axis.

In order to eliminate the differences in the rotation caused by the swimmers' anthropometrical characteristics the angular momentum values ($kg.m^2/s$) were normalized by dividing them their mass (kg) and the square of their standing height (m). Furthermore, to facilitate the interpretation of the results values of normalized angular momentum (Nam) were multiplied by 10^3 as a consequence of the resulting results are rather small. In this regard the results of Nam are expressed in units $s^{-1}.10^{-3}$ (Dapena, 1980; Hinrichs, 1987; Kwon, 1996; Yeadon, 1990) .

Statistical analysis

The normality and homocedasticity assumptions were confirmed by a Kolmogorov-Smirnov and the Levene test. A cluster analysis using the Ward method with squared Euclidean distances was applied to identify different strategies of Nam development on the block. In order to detect differences in the Nam profiles, angular, temporal and kinematic variables were grouped accordingly to each strategy of Nam. Males and females were included together in the analysis to increase the statistical power. As a consequence of early studies showed differences by gender in the temporal and kinematic variables included in this analysis (Thanopoulos et al., 2012; Tor et al., 2014), z-scores were calculated using the means and standard deviation of each gender respectively to exclude possible gender effects. One-way analysis of variance (ANOVA) with Bonferroni's post hoc test was used to identify the differences between the clusters. The statistical analysis was performed using SPSS v 19.0 software. Statistical significance was set at $p < 0.05$.

b. Results and discussion

To our knowledge, this is the first study on the biomechanics of swim starts to evaluate the time course and interdependences of the angular momentum about the mediolateral body axis during the take-off movement on the block. The results show that the Nam development is associated with body positioning during the resting stance, specifically the knee angle of the front leg and the upper limbs' angular displacement. As consequence of higher Nam values on the block, the swimmers were able to achieve shorter time to 5 m values. In contrast, Nam was unaffected by the hip angle during the block phase.

Four different Nam patterns were identified in the cluster analysis (figure 2I.1): cluster 1 consists of 15 swimmers (8 males and 7 females) and is characterised by a slight decrease of Nam values before at hands-off (with Nam values: 103.5 ± 4.1 $s^{-1}.10^{-3}$). Cluster 2 consists of 6 swimmers (5 males and 1 females) and exhibits a Nam pattern similar to that of cluster 1. However, for this cluster, longer decreases in the Nam values are present at hands-off, with the smaller Nam at take-off 81.8 ± 11.3 $s^{-1}.10^{-3}$. Cluster 3 (7 males and 1 females) shows the largest Nam values at the beginning of the block phase. Subsequent to the hands-off in this cluster, minor increases of the NAM values were detected compared with the other clusters with values of 91.4 ± 10.3 $s^{-1}.10^{-3}$ at take-off. Cluster 4, with 4 male and 3 female swimmers, showed the largest Nam values at take-off (132.5 ± 5.3 $s^{-1}.10^{-3}$). The movement pattern in this cluster can be characterised by a Nam that was consistent between the starting signal and the toe-off. Regarding the NAM values at take-off, one-way ANOVA showed significant differences between cluster 4 and clusters 1 ($p < 0.001$), 2 ($p < 0.05$) and 3 ($p < 0.001$). Further differences were also observed between cluster 1 and cluster 2 ($p < 0.05$).

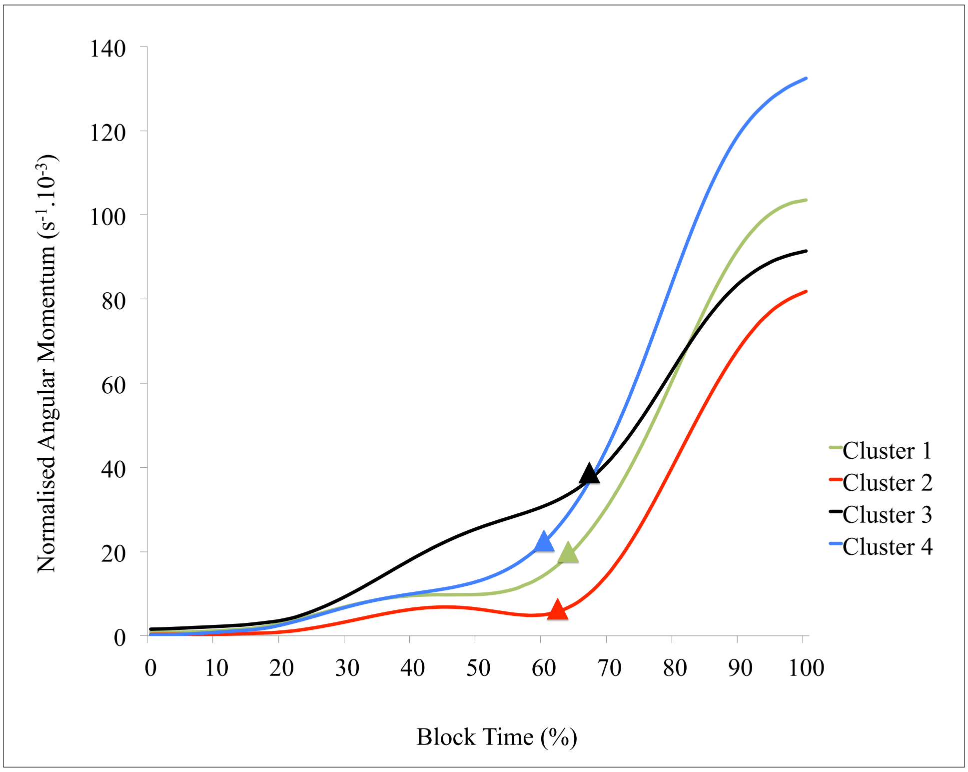

Figure 2I.1. Strategies for the development of angular momentum on the OSB11 and their standardised values (triangles correspond correspond to the take-off instant).

Differences in the Nam development between the four clusters were associated with differences in the front knee angle at starting position and differences in the upper limbs movement. Comparable mean curves and values at starting position were obtained in the hip angles for both the front leg ($F_{3,32} = 0.70$; $p = 0.557$) and rear leg ($F_{3,32} = 0.79$; $p = 0.509$) (Figure 2I.2). However, larger differences in the front knee angle at the starting position were found among the four clusters with near-significant differences ($F_{3,32} = 2.82$; $p = 0.054$) (figure 2I.2). Cluster 4 showed the largest front knee angle (cluster 1: 126.9 ± 12.1°, cluster 2: 120.9 ± 6.4°, and cluster 3: 122.4 ± 13.5°, cluster 4: 138.7 ± 16.2°); however, no statistically significant differences between cluster 4 and the other clusters were obtained in the Bonferroni's post hoc test ($p > 0.05$).

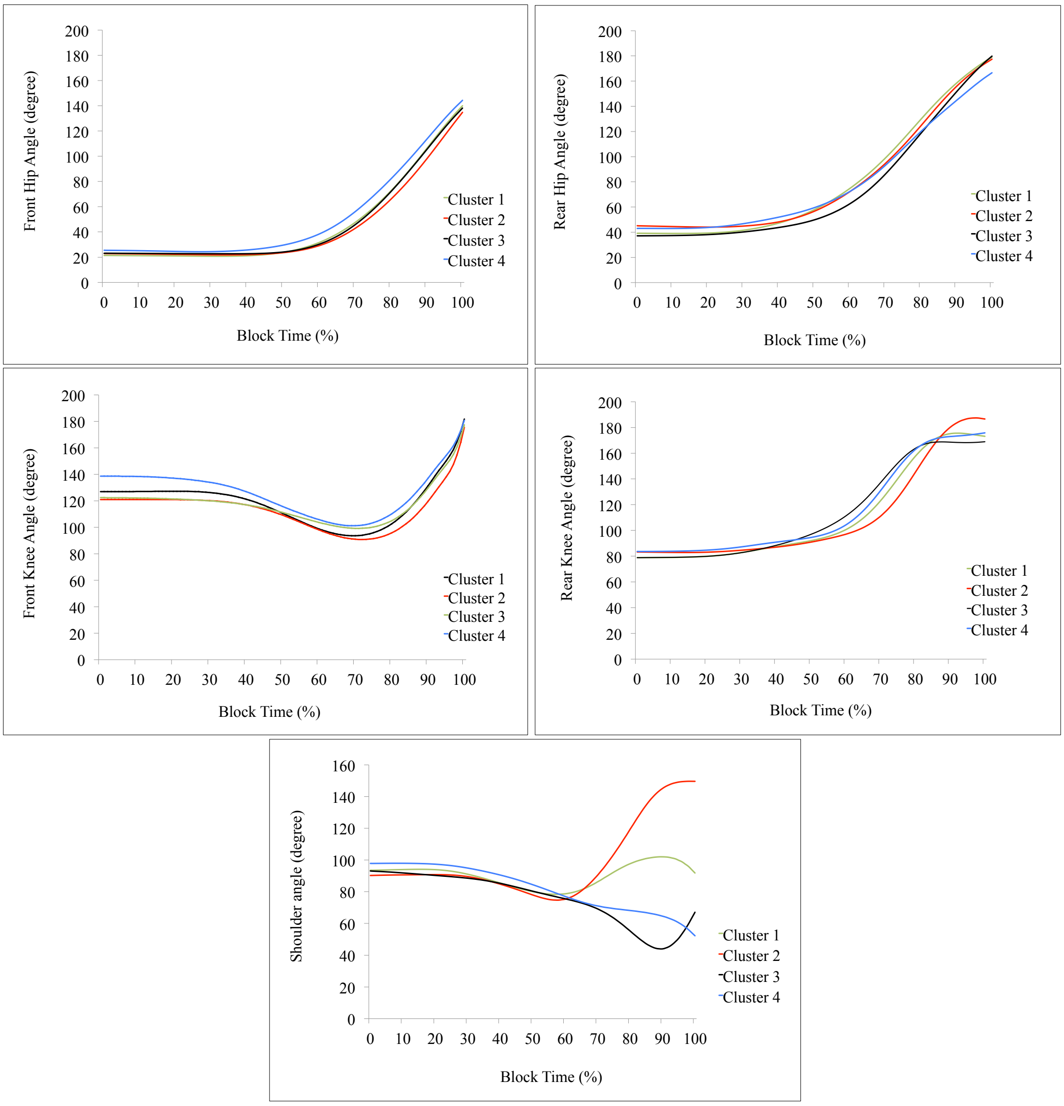

Figure 2I.2. Differences in the angular variables (knee and hip in front and rear leg and shoulder joints) for each cluster with standardised values.

In spite of the differences did not reach significant levels, we assume that larger front knee angle values imply larger Nams at take-off. In Figure 2I.3, this association can be seen in the Nam vs. body angle curves. Across all clusters, during the block phase, lower front knee angle values implied a decrease in the Nam values, and vice versa. According to Slawson et al. (2012), front knee angles between 135° and 145° in stance position facilitate the application of large forces against the platform. Strictly speaking, the angular momentum is obtained through external forces acting upon the body, which are produced while the body is in contact with the ground. Consequently, increasing the applied force will produce larger Nam values at take-off.

No differences among the clusters were found in the one-way ANOVA scores for the association between the Nam and the rear knee angle ($F_{3,32} = 0.45$; $p = 0.718$). However, in this study, the swimmers adopted a preferred stance position relative to the back plate such that rear knee angle values between 75° and 85° resulted. These rear knee angle values seem to represent an optimal range for producing greater force levels, as Slawson et al. (2012) suggested. These findings seem to indicate that rear knee angle values over 85° or below 75° will likely affect the force produced on the back plate and consequently the Nam values. A further analysis of different stances of the back plate is necessary to confirm the influence of the rear knee angle on the Nam.

The one-way ANOVA results showed no significant differences in the shoulder angle ($F_{3,32} = 2.12$; $p = 0.117$) and no significant differences between the clusters at take-off on the Bonferroni's post hoc test (cluster 1: 91.8 ± 93.3°, cluster 2: 149.6 ± 14.8°, cluster 3: 67.1 ± 41.8° and cluster 4: 52.2 ± 84.6°). In contrast, there were differences between the clusters in the angular displacement of the upper limbs between the hand take-off and the toe-off (figure 2I.2).

The results for upper limb movement reveal an association between low arm movement and larger Nam values at take-off. In contrast, a forward arm displacement was associated with lower Nam values (Figure 2I.3). A small variability in shoulder angle between the hands-off and the toe-off was observed in cluster 4, in which the swimmers kept their arms in a parallel position relative to the trunk during the block phase and had an shoulder angle of 52.2 ± 84.6°at take-off. Similar arm position was observed in cluster 1. However, for this cluster a slightly increase in the shoulder angle was observed on the block with values at take-off of 91.8 ± 93.3°. A close to perpendicular arm position relative to the trunk was observed earlier by Seifert et al. (2010). This technique was denoted as flight start. In their study, however, angular momentum values were not evaluated. In another study, Vantorre, Seifert, Fernandes, VilasBoas, & Chollet (2010a) analysed the angular momentum at take-off in different start styles. Their findings suggest that lower shoulder angle values facilitates forward body rotation and consequently increases the angular momentum. Consistent with the results of these authors, our results seem to indicate that forward displacements of the upper limbs during the block phase are associated with lower Nam values. The swimmers in cluster 2 showed the large arm displacements with a forward displacement of the upper limbs during the block phase. Likewise, this cluster obtained the largest shoulder angle (149.6 ± 14.8°) at take-off and the lowest Nam values. This finding corresponds to those of Seifert et al. (2010) and Vantorre et al. (2010a) regarding the pike start. Moreover, two different phases relative to arm displacement were observed in the second upper limb movement profile in clusters 3. A backward upper limbs displacement characterised the first phase; this movement profile showed the largest Nam compared with the other clusters. In the second phase, a forward upper limb displacement was found along with a halt in Nam production until toe-off with a shoulder angle at take-off of 67.1 ± 41.8°. This pattern has been identified in the studies by Seifert et al. (2010) and Vantorre et al. (2010a) and is called the flat start. Moreover, it is important to note that large standard deviation values were present in the shoulder angle at take-off in clusters 1, 3 and 4. However, no differences in upper arm movement strategies were detected among the clusters. In this regard, further 3D arm movement analyses seem necessary to detect different arm movements, such as circular arm movements, that a 2D analysis cannot properly identify.

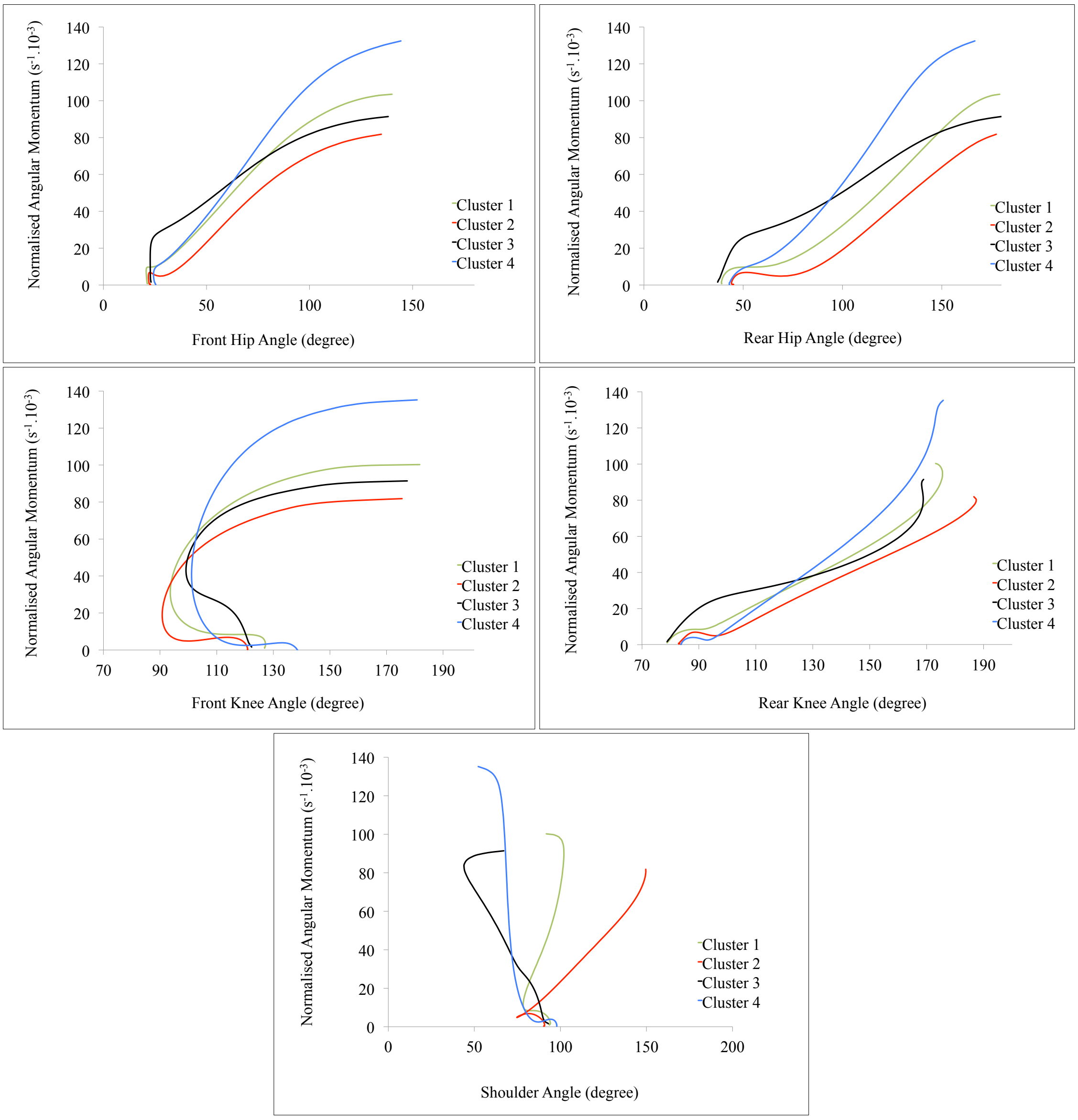

Figure 2I.3. Relationship between the development of normalised angular momentum and the hip angle, knee angle and shoulder angle in the block phase of the kick-start.

The different time courses of Nam development were associated with different magnitudes of temporal and kinematic variables (table 2I.1). The larger Nam values were associated with the best performance in the block phase and the flight phase for the kick-start. Significant differences were found for rear take-off time ($F_{3,32} = 10.82$; $p < 0.001$); time to hands-off ($F_{3,32} = 2.96$; $p = 0.05$); block time ($F_{3,32} = 6.78$; $p < 0.001$); entry time ($F_{3,32} = 7.62$; $p < 0.001$); time to 5 m ($F_{3,32} = 6.55$; $p < 0.001$) and entry distance ($F_{3,32} = 4.74$; $p < 0.05$).

Significant deviations were found in the rear block time, block time, entry time, entry distance and time to 5 m in cluster 4 compared with the cluster 1 and 2. The temporal advantages obtained on the block for cluster 4 were associated with the capacity to more quickly develop large force levels, which has been reported as the main advantage of the best kick-start performances. Previous research shows that short swim start times are mainly determined by short block times or large horizontal take-off velocities (Benjanuvatra, Edmunds, & Blanksby, 2007; Vantorre et al., 2010a). These studies, which were conducted on OSB9 blocks, suggest that short block times and large horizontal take-off velocities are mutually exclusive, as strong horizontal impulses would require large horizontal force amplitudes over time. However, in our study using the OSB11 block, the swimmers in cluster 4 were able achieve a large force amplitude with short block times. We associate this advantage with the large front knee angle values at stance found in cluster 4. In concordance with Seifert et al.(2010) the largest advantages observed on the block lead to shorter entry time and entry distance for cluster 4 than for cluster 1 and 2. Consequently, cluster 4, which showed the highest Nam values at take-off, reached the 5 m distance in a shorter time.

Furthermore, there were significant differences between cluster 3 and cluster 1 and 2 on the block performance. Cluster 3, which showed the largest Nam values at the beginning of the block phase, revealed shorter rear block time. In contrast, only significant differences were observed relative to cluster 2 in the block time. These advantages were associated with differences in the shoulder angle. Seifert et al. (2010) found a relationship between lower shoulder angle and shorter time on the block. In agreement with these authors, the smallest angular displacement of the upper limbs seem lead to advantages in the rear block time for cluster 3 than for cluster 1 and 2. Before at take-off, cluster 3 increased the shoulder angle while cluster 1 showed a small arm displacement. These differences seem to reduce the temporal advantages observed in the rear take-off.

Table 2I.1. Mean, standard deviation (SD), z-scores and significant obtained in the temporal and kinematic parameters.

	Cluster 1		**Cluster 2**		**Cluster 3**		**Cluster 4**	
	mean ± SD	z-score	mean ± SD	z-score	mean ± SD	z-score	mean ± SD	z-score
Rear block time (s)	0.63 ± 0.55^{3,4}	0.31	0.70 ± 0.09^{3,4}	1.08	0.53 ± 0.08^{1,2}	-0.60	0.52 ± 0.05^{1,2}	-0.91
Hands-off (s)	0.47 ± 0.07	0.26	0.50 ± 0.10	0.48	0.45 ± 0.07	-0.13	0.38 ± 0.09	-0.83
Block time (s)	0.76 ± 0.06^{4}	0.28	0.82 ± 0.10^{3,4}	0.93	0.68 ± 0.07^{2}	-0.49	0.66 ± 0.06^{1,2}	-0.84
Flight time (s)	0.23 ± 0.07	0.09	0.25 ± 0.03	0.34	0.21 ± 0.06	-0.24	0.21 ± 0.03	-0.22
Entry time (s)	0.99 ± 0.09^{4}	0.30	1.06 ± 0.10^{3,4}	0.96	0.89 ± 0.06^{2}	-0.56	0.88 ± 0.04^{1,2}	-0.83
Time to 5 (s)	1.66 ± 0.12^{4}	0.47	1.61 ± 0.124	0.56	1.49 ± 0.12	-0.51	1.52 ± 0.16^{1,2}	-0.90
Horizontal take-off velocity (m/s)	4.22 ± 0.23	-0.13	4.34 ± 0.19	-0.20	4.52 ± 0.24	0.59	4.21 ± 0.46	-0.22
Vertical take-off velocity (m/s)	-1.12 ± 0.41	-0.02	-1.13 ± 0.30	-0.14	-1.12 ± 0.45	-0.16	-0.97 ± 0.17	0.34
Entry distance (m)	2.68 ± 0.41^{4}	0.41	2.85 ± 0.14^{4}	0.43	2.54 ± 0.61	-0.27	2.02 ± 0.67^{1,2}	-0.94
Take-off angle (°)	35.44 ± 5.70	0.17	36.37 ± 2.63	0.66	30.38 ± 6.50	-0.31	29.16 ± 2.58	-0.58

2.II. Biomechanical evaluation of angular momentum during the kick-start technique

The angular momentum is an important parameter in the swim start performance due to its implication in the body rotation along the flight and its influence in the body position at water entry. The angular momentum generated in contact with the starting block determines the rotational motion during a flight phase. Likewise, this rotational motion is not just limited to an aerial phase but it continues when the hands make contact with the water. However, no study evaluated its performance beyond the values obtained at take-off instant. The purpose of this study was to examine and describe different angular momentum developments of six elite swimmers during the kick-start technique. This study represents the first that shows the evolution of angular momentum about the mediolateral body axis from the starting signal to the gliding phase of a swim start. The results showed that the body rotation about the mediolateral axis during the kick-start changes the direction along the course of time. A clockwise rotation was observed during the block phase and flight phase while at the first contact with the water a rotation in a counterclockwise direction was showed. On the block, the clockwise rotation was associated with a forward direction of the body with the objective to leave the block and reach the water. During the flight, the amount of angular momentum obtained on the block remains constant. The body rotation is produced by an upward displacement of the lower limbs that lead different body positions at the first contact with the water. At water entry, the rotational direction changed to a counterclockwise rotation. This variation was associated with an upward displacement of the upper body and the performance of a dolphin-kick after the feet immersion in order to change the vertical body position at hands entry to a horizontal displacement during the gliding phase. Larger counterclockwise rotation under the water was suggested important in order to reduce the loss of horizontal velocity.

a. Methodology

Participants

Six elite swimmers (1 female and 5 males) from the German National Team volunteered to participate in this study. Participant characteristics are presented in the table 2II.1. All participants had competed in sprint freestyle, breaststroke or medley races at Olympic or World level. They had used the starting block with back plate OSB11 in training and competition. Consequently all swimmers had a remarkable experience in the kick-start performance. The participants signed an informed consent and the University Ethics Committee approved the procedures used for this analysis.

Table 2II.1. Participant characteristics including the mean and standard deviation (SD) for the total sample.

	Age (years)	**Height (cm)**	**Mass (kg)**	**FINA Points Scoring (Main event)**
Subject 1	29.0	193.0	94.3	942.0
Subject 2	23.0	189.0	87.0	939.0
Subject 3	31.0	177.0	67.1	934.0
Subject 4	28.0	185.0	80.5	946.0
Subject 5	21.0	196.0	85.0	905.0
Subject 6	17.0	187.0	85.5	771.0
Mean	24.0	187.8	83.2	933.2
SD	5.4	6.6	9.1	16.4

Experimental procedure

Prior to data collection, individual warm-up programmes were performed. For the testing session the swimmers were instructed to perform the kick-start from a starting block OSB11 in two different starting positions. Firstly swimmers adopted their preference position on the block with their habitual back plate position and rear leg. Then, participants were instructed to lower their hip height and descend the centre of mass (CoM) keeping their habitual back plate position and rear leg. Each start was followed by 15 m freestyle at maximal velocity. Starting signal was made verbally conformed to FINA swimming rules (SW 4.2). An external trigger connected to the cameras system was used to start the capture.

Figure 2II.1 depicts the cameras distribution for the data collection. Three-dimensional kinematic data (50Hz) were collected using five over water cameras and one underwater camera (Oqus 3+, Qualisys AB, Gothenburg, Sweden) and recorded using Qualisys Track Manager (Qualisys AB, Gothenburg, Sweden). Prior to each session, a capturing volume (height × depth × width, 2 x 3 x 1.5 m) was calibrated with average tracking residuals of < 0.99 mm for each camera for a 750.5 mm wand lenght. Participants wore 22 spherical reflective markers to define 14 body segments. Vertex, ear and cervical landmarks defined the head segment. The shoulder and hip landmarks on the right and left side defined the trunk. Upper limbs were defined by the shoulder, elbow, wrist, finger tip and fingertip landmarks. Lower limbs were defined by the hip, knee, ankle, heel and finger toe landmarks. Preceding each session, a static calibration trial was recorded with the participants standing in an anatomically neutral upright position next to the starting block.

Above the water data were processed and analysed using Visual3D (C-Motion, Germantown, MD, USA). Raw kinematic marker trajectories were interpolated and smoothed with a fourth-order zero-lag Butterworth low-pass filter with a cut-off frequency of 6 Hz. The whole-body model was represented as an articulated multi-segment system with 14 rigid segments (head, thorax/pelvis, upper arms, forearms, hands, thighs, shanks and feet) using inverse-kinematics (IK). Segment inertia parameters were obtained from de Leva (1996).

Two-dimensional kinematic data (100Hz) were collected underwater using an Oqus-underwater camera (Qualisys AB, Gothenburg, Sweden), which was simultaneously run by Qualisys Track Manager (Qualisys AB, Gothenburg, Sweden). Eleven anatomical points were identified on the right side of the body to define a body model of eight body segments based on de Leva (1996). Post-hoc analysis of the 2D-data was performed using a SIMI-Motion Analysis System (Simi Reality Motion Systems GmbH, Unterschleißheim, Germany).

Due to restricted visibility under the water, the body segment locations could not be assessed through the segment end-points. Instead, the mid-lines of the segments were determined through a simple regression technique. For that purpose, three representative points on the presumed mid-line of a body segment were digitized. While the end-point we not visible for most segments, mid-lines could be properly identified. In this regard, the joint coordinates were calculated by the intersection of the mid-lines representing the adjacent segments. Given the particular importance of the trunk, this segment was treated with four representative points to determine a cubic spline function (Fischer, 2013).

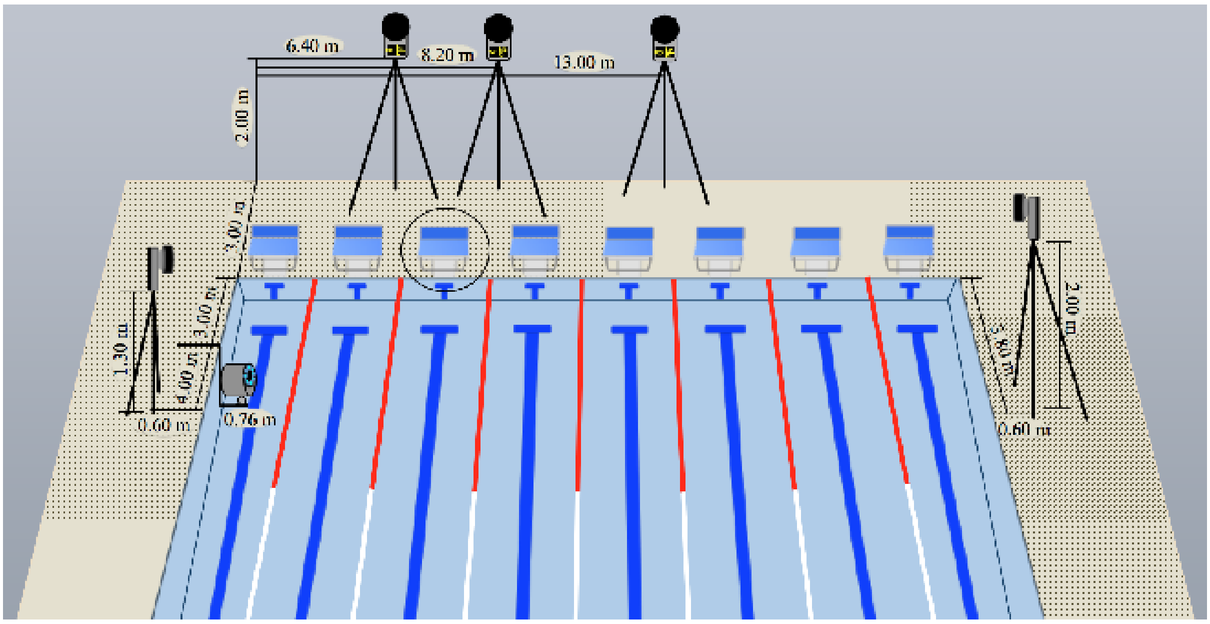

Figure 2II.1. Cameras distribution for the data collection.

Data analysis

The kick-start was defined by three phases: 1) **block time** (%), time from the starting signal until the swimmers' feet leave the block; 2) **flight time** (%), time from the feet leave the block until the hands make contact with the water surface; and 3) **entry time** (%), time from the first contact with the water until the total feet immersion; and 4) **glide time** (%), elapsed time between the total feet immersion to the first perceptible undulatory underwater movement. All phases were expressed as a proportion of the matching times. For a detailed evaluation about the angular momentum development further variables were included: **horizontal CoM velocity** (m/s), magnitude of the horizontal velocity of the CoM vector at take-off; **vertical CoM velocity** (m/s), magnitude of the vertical velocity of the CoM vector at take-off; **shoulder angle** (°), angle between the hip, shoulder and elbow; **hip angle** (°), angle between the hip, shoulder and knee for the front leg. This angle was measured as the average between the front and rear leg.

The **total angular momentum** (H) of the swimmer's body about the mediolateral body axis was obtained by adding the angular momenta of all the segments into which the body was divided according to the centre of mass model (Kwon, 1996).

$$H = \sum_{i} (m_i r_i \times v_i + I_{CM} \times \omega) \qquad (2II.1)$$

Where the first term $\mathbf{m_i r_i \times v_i}$ is the angular momentum due to the translation of the CoM and where $\mathbf{m_i}$ = the mass of each segment; $\mathbf{r_i}$ = the position of the each segment and $\mathbf{v_i}$ = the velocity of each segment. The second term $\mathbf{I_{CM} \times \omega}$ belongs to the angular momentum due to the rotation of the body about its CM; here $\mathbf{I_{CM}}$ is the momentum of inertia of the segment and $\boldsymbol{\omega}$ = the angular velocity of the segment.

In order to eliminate the differences in the rotation caused by the swimmers' anthropometrical characteristics the angular momentum values (kg.m^2/s) were normalized by dividing them their mass (kg) and the square of their standing height (m). Furthermore, to facilitate the interpretation of the results values of normalized angular momentum (Nam) were multiplied by 10^3 as a consequence of the resulting results are rather small. In this regard the results of Nam are expressed in units $s^{-1}.10^{-3}$ (Dapena, 1980; Hinrchs, 1987; Kwon, 1996; Yeadon, 1990).

Statistical analysis

The mean and standard deviation were calculated for each parameter. To evaluate the different movement strategies in Nam development between the starting signal and the glide phase, a cluster analysis using the Ward method with squared Euclidean distances was applied. The statistical analysis was performed using SPSS v.19.0 software. Given the main objective of this study is exploratory, further statistical treatment of the results has not been performed. Nam development will be described without additional support from test of statistical significance.

b. Results and discussion

Previous studies including data of angular momentum for the different types of swim starts reported values of angular momentum at take-off and compared the results for the different start techniques (McLean et al., 2000; Vantorre et al., 2010; Vantorre et al., 2011). Our study shows the development of the angular momentum about the mediolateral body axis during the block, flight, entry and gliding phase of a swim start. To our knowledge this is the first study that provides complete data of angular momentum from the starting signal to the glide phase.

Six elite swimmers and a total of twelve trials of the kick-start technique were examined to evaluate the Nam development. Based on the right-handed rule, positive values of Nam indicate a clockwise rotation while negative values represent a counterclockwise rotation. Three different Nam profiles with different values at take-off and different curves during the entry and glide phase were observed (figure 2II.2). In spite of each swimmer performed two kick-start techniques with different heights of CoM at starting position, similar Nam development was found in both trials. Only the subject 2 showed a different Nam development for the kick-start with higher and lower CoM position. Consequently, cluster 1 consists on 2 swimmers and 3 trials (two trials performed by the subject 1 and one trial performed by the subject 2). Cluster 2 consists on 2 swimmers and 3 trials (one trial performed by the subject 2 and two trials belong to subject 3) and cluster 3 with 3 swimmers and six trials.

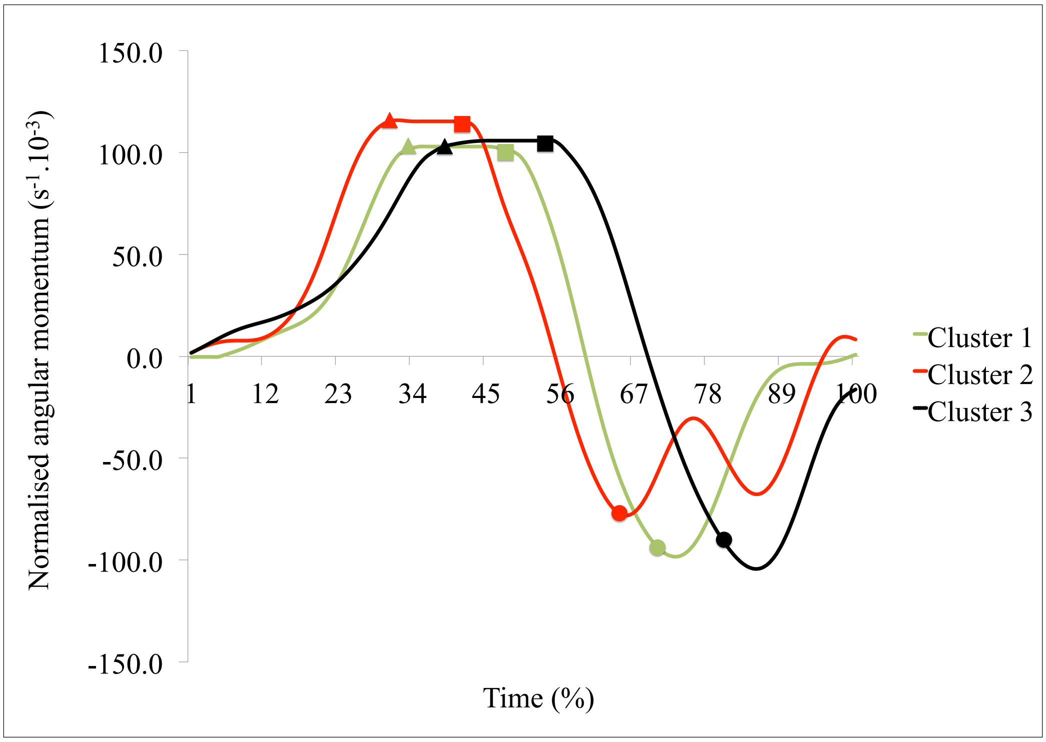

Figure 2II.2. Strategies for normalized angular momentum developed between the starting signal and the gliding phase during the kick-start technique with standardized values (triangles correspond correspond to the take-off instant, squares correspond to the hands entry and circles correspond to the feet immersion instant).

The results showed a gradual increase of Nam during the block phase for the three clusters. A positive increase of Nam indicates a body rotation in a clockwise direction on the block and consequently, the line of action of the ground reaction force passed behind the CoM throughout the overall block phase (Newton's second law). This clockwise rotation was associated with a forward direction of the body in order to leave early the block and reach the water.

In spite of the three clusters showed the same rotational direction on the block, it is important to note that each cluster showed different Nam development. Cluster 1 and cluster 3 showed more gradual increase of Nam along the block phase and cluster 2 presented a faster and higher increase of Nam on the block with larger values at take-off (cluster 1: 102.93 ± 7.01 $s^{-1}.10^{-3}$; cluster 2: 115.30 ± 2.74 $s^{-1}.10^{-3}$; cluster 3: 105.40 ± 9.74 $s^{-1}.10^{-3}$). These differences were associated with larger ground reaction force (principally the horizontal component) passing behind the CoM on the block for cluster 2.

The angular momentum is created through the force developed by the swimmer against the block, the perpendicular distance from the CoM to the line of action of the force (i.e. moment arm) and the time over which the rotational force is acting. Since the three clusters showed a clockwise rotation and similar body position on the block, we assumed that the moment arm was similar among the three clusters. In contrast, cluster 2 showed shorter block time than cluster 3 and similar values than cluster 1 (cluster 1: 32%; cluster 2: 32%; cluster 3: 37%). Consequently, the swimmers in cluster 2 had to develop larger force levels on the block in order to get larger Nam values at take-off with shorter or similar block time than cluster 3 and 1. The horizontal velocity developed on the block supports these results. Cluster 2 presented larger and faster horizontal velocity development on the block than cluster 1 and cluster 3, while the vertical velocity was higher for cluster 1 and cluster 3 (figure 2II.4).

On the block, the arms displacement is an important factor to increase or reduce the rotational acceleration and consequently the rotational force. Early studies suggested that forward arm swing decreases the body rotation while a backward displacement increases the rotation on the block (Vantorre, Chollet, & Seifert, 2014). The analysis of the shoulder angle carried out for the three different profiles of Nam during the kick-start showed differences in the arms displacements on the block. The swimmers in cluster 1 and 3 produced a backward displacement of the arms on the block with smaller shoulder angle values at take-off. Cluster 2 presented a backward and forward displacement on the block with larger shoulder angle at take-off (figure 2II.3). In spite of different arms displacement for each cluster, it is important to note that all clusters showed shoulder angle values around 80° throughout the most of the block phase. Differences in the shoulder angle values among three clusters only increased few seconds early at take-off. In this regard, the differences in the shoulder angle shown in this study seem not to be enough to influence the development of the angular momentum on the block.

During the flight phase, the Nam values obtained at take-off remained constant. Based on the Newton's first law, the angular momentum of a body remains constant unless a net external torque is exerted upon de body. However, along the flight phase and based on the amount of angular momentum obtained at take-off instant, the swimmers can move one part of the body in one direction and other parts in the opposite direction to increase or reduce the rotational velocity and change the body position (Dapena, 2000). Early studies showed that for kick-start the main rotational movements are produced by an upward displacement of the lower limbs (clockwise rotation) while the trunk performs a slightly movement in the anticlockwise direction along the flight (McLean et al., 2000; Taladriz, De la Fuente-Caynzos, & Arellano, 2016; Vantorre et al., 2010). These movements increase the momentum of inertia and reduce the rotational velocity (they distribute the mass further to the axis of rotation) leading to an entry into the water in a more straight and controlled position.

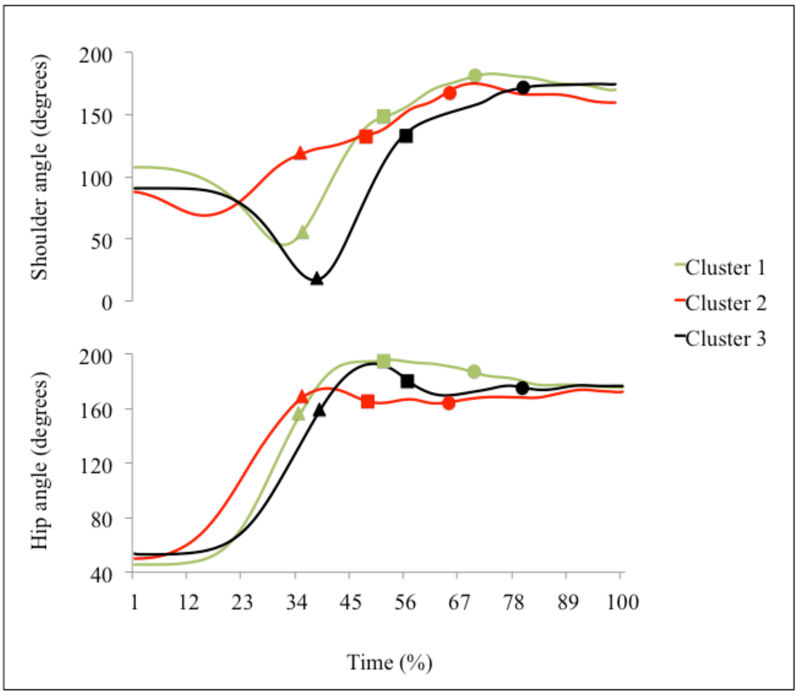

Figure 2II.3. Differences in the angular variables (shoulder and hip joints) for each cluster of normalized angular momentum during the kick-start with standardized values (triangles correspond correspond to the take-off instant, squares correspond to the hands entry and circles correspond to the feet immersion instant).

Besides of the amount of angular momentum obtained at take-off, the time invested in the air is a relevant variable to increase the body rotation. Longer flight time implies longer time to rotate (i.e. longer time to perform the upward displacement with the lower limbs) leading to a more pike position at the first contact with the water (Vantorre et al., 2014). In this regard, cluster 2 with the largest Nam values at take-off and shorter flight time (cluster 1: 16%; cluster 2: 14%; cluster 3: 19%) seems to generate smaller body rotation along the flight phase than cluster 1 and 3. This conclusion was also supported by the results obtained for the hip angle at take-off and at first contact with the water. The swimmers of the cluster 2 showed a hip angle variation of 10.8° (hip angle at water entry; 168.2° - hip angle at take-off; 157.5°) while the cluster 1 and cluster 3 showed a hip angle variation of 56.2° and 32.8°, respectively (Cluster 1: hip angle at water entry; 194.4° - hip angle at take-off; 138.2°; cluster 3: hip angle at water entry; 181.7° - hip angle at take-off; 148.9°). Differences in the vertical velocity at take-off seem to be the reason of shorter flight times and consequently smaller body rotations. For cluster 2, the smallest vertical velocity values led a downward body position at take-off. In contrast, cluster 1 and cluster 3 presented a flatter body position at take-off (cluster 1: -0.53 ± 0.45 m/s; cluster 2: -1.47 ± 0.74 m/s; cluster 3: -0.67 ± 0.54 m/s).

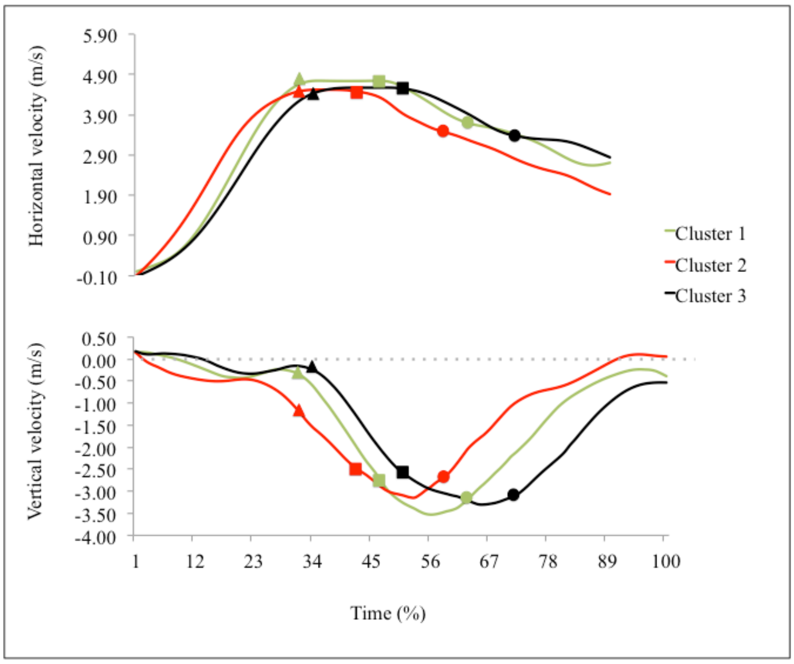

Figure 2II.4. Differences in the horizontal and vertical velocity for each cluster of normalized angular momentum during the kick-start with standardized values (triangles correspond correspond to the take-off instant, squares correspond to the hands entry and circles correspond to the feet immersion instant).

At the first contact with the water the Nam values decreased until to reach negative values. In this regard, the clockwise rotation observed on the block and during the flight phase turned into a rotation in a counterclockwise direction as the entry into the water progressed. For each cluster, the drop of Nam values started at the first contact with the water and reached the peak negative values after the total feet immersion (figure 2II.2).

The decreasing of the Nam development with positive values indicated an absence of body rotation. This decreasing in the clockwise rotation was associated with the entry into the water of the upper body. When the hands make contact with the water, the swimmers adopt a vertical body position, with a higher lower limbs position relative to the upper body. As the upper body enters into the water, the body trajectory must continue being vertical in order to reach an optimal depth. Consequently, the upper body remains without any movement. The only movements were shown for the lower limbs by slightly upward or downward displacements in order to entry into the water in a straight position to reduce the water resistance. However, these movements did not generate any body rotation about the mediolateral axis. Variations in the hip angles values confirmed the lower limbs displacement (Figure 2II.3).

The negative Nam values were associated with an upward displacement of the upper body as the entry into the water progress and a downward displacement of the lower limbs after the feet immersion. As the entry into the water progressed, the swimmers must transfer the vertical body position adopted when the hands made contact with the water to a horizontal direction in order to follow a horizontal trajectory during the gliding phase. With this purpose, the swimmers perform an upward displacement with the upper body between the instant when the upper body is submerged and the feet immersion (figure 2II.5). These conclusions are supported by the hip angle curves. When Nam values were negatives, a slightly increase in the hip angle values was observed for cluster 2 and cluster 3. However, cluster 1 showed a decrease of the hip angle at this instant. It is suggested that for this cluster a hyperextended back position at water entry lead a downward leg displacement that causes the counterclockwise rotation (figure 3b). The anticlockwise rotation supposes a fast increasing in the vertical velocity after the instant when the hands made contact with the water (figure 2II.4). In contrast, the horizontal velocity decreased slightly as a consequence of the water resistance but the values were maintained without reaching zero value (figure 2II.4). These results confirm the transfer of the vertical body direction when the hands made contact with the water to a horizontal direction.

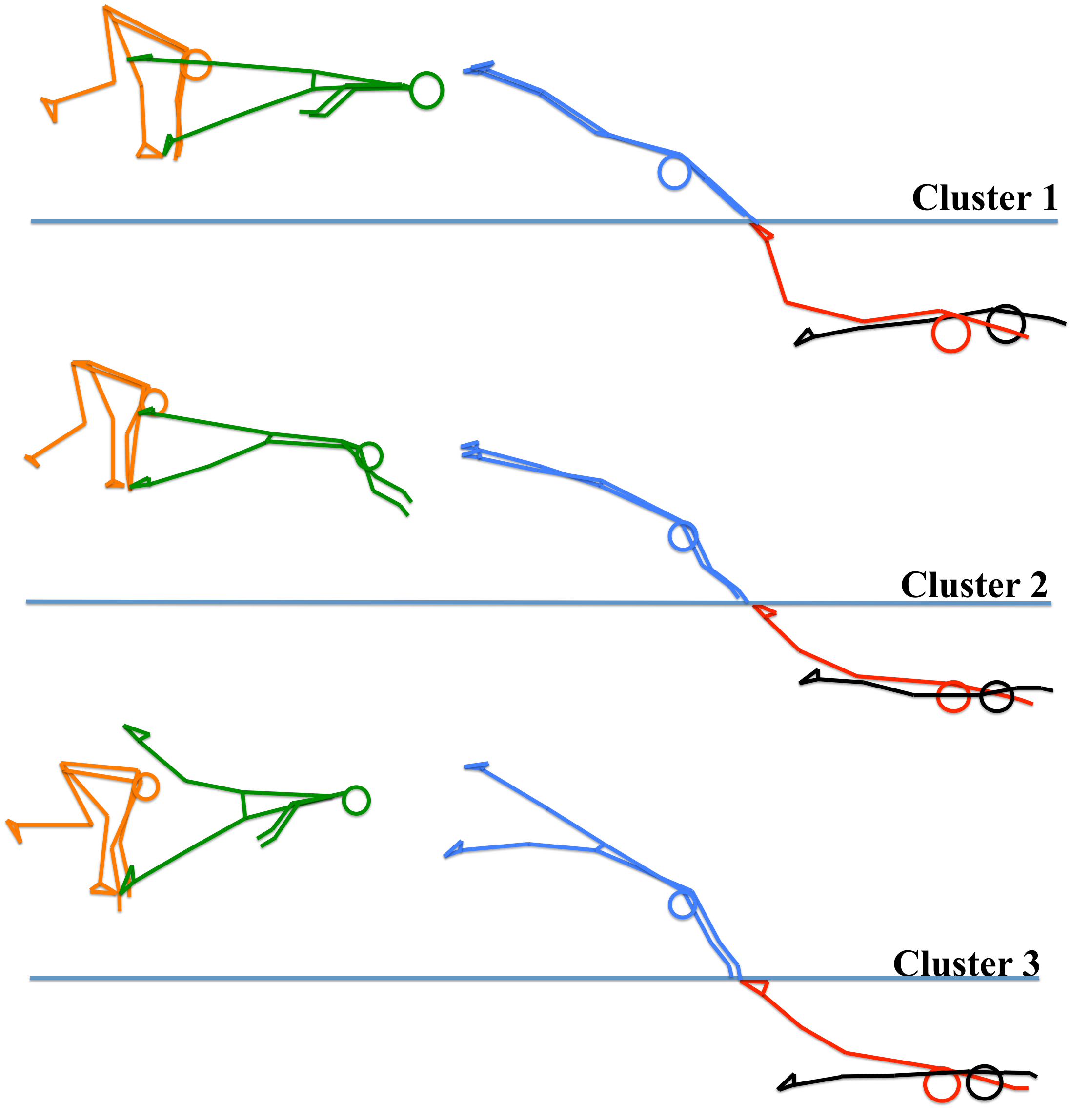

Figure 2II.5. Graphical description of the motions developed in each cluster between the starting signal and the gliding phase for kick-start technique. Each figure belongs to one subject included in the matching cluster.

After the feet immersion, the negative Nam values continued increasing, which indicated that the body rotation continued in a counterclockwise direction. At this instant, the upper body is positioned mainly in a horizontal position, in agreement with the gliding direction, and the lower limbs are positioned in a vertical position relative to the upper body, with the feet close to the water surface (figure 2II.5). Consequently, after the feet immersion the swimmers performed a downward displacement with the lower body in order to adopt a straight body position. This lower limbs displacement lead to a counterclockwise rotation between the feet immersion and the horizontal body position (figure 2II.2).

Different peak negative values of Nam were observed between each cluster. Cluster 1 (-98.88 ± 9.02 $s^{-1}.10^{-3}$) and cluster 3 (-107.22 ± 11.20 $s^{-1}.10^{-3}$) showed the largest negative values relative to the cluster 2 (-83.63 ± 6.94 $s^{-1}.10^{-3}$) (figure 2). These differences indicated different downward displacements of the lower limbs after the feet immersion. It was suggested that cluster 3 with larger counterclockwise rotation performed the largest displacement (i.e. larger dolphin-kick) followed by cluster 1 and cluster 2. In this regard, larger counterclockwise rotation seems to be important to reduce the loss of horizontal velocity produced as a consequence of the water resistance during the water entry. Lower loss of horizontal velocity was found for cluster 1 and cluster 3, which showed larger negative peak values of Nam (cluster 1: 0.95 ± 0.17 m/s; cluster 2: 1.60 ± 0.07 m/s; cluster 3: 0.53 ± 0.13 m/s). In contrast, cluster 2 with smaller negative values showed a larger decrease of horizontal along the entry phase (figure 2II.4).

Differences in the peak negative values of Nam were associated with differences in the body rotation during the flight phase and consequently with differences in the hip angle obtained at the first contact with the water. Cluster 1 and cluster 3 showed larger body rotation at flight phase and consequently a hyperextended back position and a straight body position at the instant to reach the water, respectively (cluster 1: 197.40 ± 14.15°; cluster 3: 182.39 ± 7.36°). In contrast, cluster 2 showed lower body rotation and smaller hip angle values at the instant of the first contact with the water (cluster 2: 167.81 ± 10.27°) (Figure 2II.3). Larger hip angle at this instant makes that swimmers must increase the upward displacement of the upper body in order to obtain a horizontal body position during the glide phase. Consequently, at feet immersion larger hip angle will be obtained and therefore larger downward displacement (i.e. more powerful dolphin-kick) with the lower limbs must be produced in order to reach a straight body position. In contrast, lower hip angle at water entry leads to flatter water entry and consequently a lower counterclockwise body rotation is enough to get the horizontal body position. These results agreed with early studies (Fischer & Kibele, 2010; Fischer & Kibele, 2014) that related larger hip angles at water entry with a powerful dolphin-kick after the feet immersion.

After the instant when the peak negative Nam values were obtained, two different profiles of Nam were developed (figure 2II.2). Cluster 1 and cluster 3 increased progressively the Nam values. A decrease in the negative Nam values indicates lost of counterclockwise rotation. In this regard, the swimmers of the cluster 1 and cluster 3 stopped the body rotation about the mediolateral axis after the feet immersion. At this instant, the displacement of the swimmers is performed in a horizontal direction corresponding to the glide phase (Figure 52II.). In contrast, cluster 2 presented alternative phases of increase and decrease Nam (figure 2II.2). An increase in the Nam values is associated with a slightly upward displacement of the lower limbs while the decrease in the Nam values were related with a downward displacement. As the Nam values increased, the hip angle also increased and conversely (figure 2II.3). As a consequence of the flatter entry into the water, the swimmers of the cluster 2 were not able to perform a dolphin-kick after the feet immersion. With the purpose to reduce the loss of horizontal velocity they tried to perform a small dolphin-kick during the gliding phase. However, this movement was not effective.

CONCLUSIONS

The studies included in this chapter provide an insight into the development of the angular momentum during the kick-start technique. Based on our findings it can be set that an optimal strategy into the development of the angular momentum is important to improve the kick-start performance.

The amount of angular momentum developed on the block is essential to perform the rotational movements required during the flight phase to obtain the greatest advantages under the water. Larger amount of angular momentum lead shorter time to 5 m due to the advantages reported over the entry into the water. It was determined that larger front knee angle increase the amount of angular momentum due to the relationship between the knee angle and the force developed on the block. Moreover, an arm position close to the trunk was shown to increase the body rotation on the block.

The main advantage of larger angular momentum on the block is that swimmers can develop larger upward displacement with the lower limbs (i.e. clockwise rotation) during the flight phase. However, an optimal balance between larger clockwise rotation on the block and an optimal body position at take-off is required to obtain larger flight time and to perform large segmental displacements.

Larger clockwise rotation during the flight phase leads to larger counter clockwise rotation at water entry and larger advantages during the gliding phase. For kick-start, the counterclockwise rotation shown after the hand made contact with the water involves larger displacements with the upper body until the feet immersion and larger downward displacement with the lower limbs after the immersion. Consequently, larger negative values of angular momentum at water entry were associated with a powerful dolphin-kick after the feet immersion and a decrease in the horizontal velocity during the gliding phase as a consequence of the water resistance.

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GENERAL CONCLUSIONS

The main purpose of this thesis has been to evaluate the characteristics and advantages provided by the kick-start technique to swimmers. As a consequence of the great relevance of the angular momentum on the start performance, it was paid a special attention to the angular momentum and body rotation generated during the swim start. With this purpose, four different studies and methodologies were performed. Based on the results of each study, the main conclusions of this thesis can be summarized as follow:

- A comparison between the kick-start and grab start was made with the goal to examine the reasons of the best kick-start performance. The great temporal advantages obtained for the kick-start technique were related with the ability to develop large forces in a shorter time. The back plate allows to swimmers to reach the maximum horizontal acceleration before the rear foot leaves the block. Consequently, similar horizontal take-off velocity is obtained at take-off in shorter time. In contrast, the grab start needed larger time on the block to obtain similar horizontal take-off velocity.

- The upward displacement of the rear leg on the block supposed an important advantage for kick-start regarding the grab start. This displacement leads to a more downward body position at take-off and a higher position of the lower limbs relative to the trunk when the hands make contact with the water (larger final body angle). Consequently, a lower loss of velocity at water entry was observed for kick-start than for grab start.

- The relationship between the block phase and flight phase variables was made with the goal to determine the key factors for an improvement of the kick-start technique.

≈ Faster and higher horizontal acceleration development on the block is the key of the best kick-start performance. This profile of the horizontal acceleration developed on the block leads a shorter block time, higher horizontal take-off velocity, longer flight phase, higher final body angle, lower loss of velocity and shorter time to 5 m.

≈ A shorter upward displacement of the rear leg is required for a longer flight phase. As a consequence of the longer flight phase, the swimmers can increase the body rotation in the air and to reach the water with a higher lower limbs position relative to the trunk. This body position reduces the loss of velocity at water entry and leads shorter time to 5 m.

- The amount of body rotation in the air depends on the amount of angular momentum at take-off. In the kick-start the body rotation in the air is mainly produced by an upward displacement of the front leg towards the rear leg with the objective to enter into the water with both legs together. In contrast, for the grab start the trunk mainly produces the rotational movement by a clockwise rotation towards the lower limbs. In spite of different rotational movements and body position at water entry, both techniques maintained the temporal differences on the block up to 5 m distance.

- An analysis of angular momentum developed on the block was made during the kick-start with the objective to identify different profiles of angular momentum at take-off, the variables implied in the development of the angular momentum and with the objective to evaluate the effect of the angular momentum on the kick-start performance. Four different profiles of angular momentum were identified on the block. The profile with larger amount of angular momentum was associated with shorter time to 5 m.

- Larger amount of angular momentum was shown dependent on higher front knee angle at starting position. These results were associated with the higher development of force that permits the higher front knee angle.

- A closer arms position to the trunk was associated with an increase of the amount of angular momentum on the block. In contrast, the amount of angular momentum is reduced when the upper limbs perform a forward displacement.

- The qualitative study of the angular momentum developed during the kick-start technique indicated that to find an optimal strategy between to increase the amount of angular momentum developed on the block and larger flight time is required to increase the body rotation along the flight phase. Larger body rotation during the flight phase by a larger displacement of the lower limbs leads to larger hip angle at the first contact with the water. This body position seems to be optimal in order to increase the counterclockwise rotation developed after the feet immersion, which was related with a powerful dolphin-kick and a decrease in the loss of horizontal take-off velocity under the water.

LIMITATIONS AND FUTURE STUDIES

Some limitation has been acknowledge in this thesis, which can be summarize as follow:

≈ The main limitation of the study I Chapter 2 was the small sample. The reduced number of participants (9 swimmers) and the large number of comparison (18 kinematic variables) required to carry out the objective of this study affected to the statistical power. In this regard, the Holm's correction adjustment was made to control for the inflation of the type I error. In spite of adjusting the critical p-values of each test, the small sample caused that just comparisons with a large effect size were shown significantly different. In spite of the small sample size was justified given the elite level of performance, for future research is recommended increase the sample size to confirm the advantages of the kick-start technique.

≈ Concerning the chapter 2, it is assumed as a limitation of the study I the use of 2D analysis to export the quantitative results. This fact implied great shoulder angle variability and the absence of significant differences in upper arm movement strategies among the clusters. In this regard, further 3D arm movement analyses seem necessary to detect different arm movements, such as circular arm movements, that a 2D analysis cannot properly identify.

≈ Another limitation can be considered the just skill level used for all studies included in this thesis. For all studies, an elite sample was used which imply that the results supported in each study are just suitable for the elite level. Consequently, it is not ensured that the differences and advantages obtained for kick-start will be maintained in swimmers with a lower level. This means that future research with several skill levels should be performed in order to evaluate the advantages of the kick-start in other populations.

≈ Likewise, the total swimming start performance is measured by the time invested between the starting signal and the mark to 15 m. Due to the influence that the water entry has on the underwater performance and the relevance of the underwater phase on the total swimming start performance, a further analysis about the effect of the different body positions at hands entry would be required to determine the advantages of each one on the underwater performance and the overall start performance.

Based on the results obtained in each study included in this thesis another **future studies** will be interesting to improve the kick-start performance and understand the angular momentum development. The main temporal advantage obtained for the kick-start technique was associated to the larger development of force in a shorter time, which permits to obtain the maximum horizontal acceleration in few seconds. In concordance with these results, the explosiveness development on the block seems to be the most relevant factor to improve the kick-start technique. Agreement with this conclusion, the application of a specific training to improve the explosive force is recommended to analyse the advantages supported to the kick-start performance.

In the study 1.I, chapter 1, contradictory results were found for the advantages obtained in the kick-start relative to the grab start and the factors required to improve the kick-start technique. The upward displacement of the rear foot on the block was shown the main advantage of the kick-start technique in order to entry into the water with a higher final body angle and reduce the loss of velocity at water entry. The displacement allows to swimmers adopt a more downward body position at take-off that facilitates the higher final body angle relative to the grab start. In contrast, Pearson’s correlation showed that larger upward displacement of the rear foot on the block affect negatively to the kick-start performance. This displacement reduce the flight phase and consequently reduce the final body angle increasing the loss of horizontal velocity at water entry and finally the time to 5 m. Based on this results, to establish the range of rear leg displacement on the block seem to be required to improve the kick-start technique.

Besides the shoulder angle, the knee angle was also established as a parameter implied in the development of the angular momentum on the block. In the study 2.I, chapter 2, it was observed that the higher front knee angle produce larger amount of angular momentum at take-off, however, no differences were found in the rear knee angle. For both, front knee angle and rear knee angle the values obtained were related with the optimal range in order to obtain the higher force development on the block. Consequently, a further study analysing the effect of larger front knee angle values at take-off as well as the effect of different rear knee angles at take-off will be interesting to ensure the effect of the lower limbs angle over the amount of angular momentum produced at take-off.

Finally, a further quantitative analysis of the angular momentum development along the block phase, flight phase and water entry is required to evaluate the advantages that the angular momentum offers to the kick-start performance.

PRACTICAL RECOMMENDATIONS

Based on the results obtained in each one of the studies included in this thesis, the following recommendations would be indicated for swimmers and coach:

* A training of the explosive force is recommended in order to increase the force developed on the block and to reduce the time invested on the block. Moreover, an increase on the force developed will increase the amount of angular momentum produced at take-off.

* Larger amount of angular momentum at take-off is required to increase the body rotation along the flight phase. With this purpose is recommended for swimmers to determine the best back plate position and the starting position that allows them to develop larger force levels. Based on the results obtained in the chapter 2.I, the swimmers must find an starting position that allows them to obtain a front knee angle around 140 degrees and a rear knee angle between 75-85 degrees.

* An arms displacement towards to the trunk between the take-off hands and the feet leave the block is recommended to increase the amount of angular momentum at take-off.

* Besides the amount of angular momentum on the block, larger body rotation during the flight is also dependent on larger flight time. With this purpose, swimmers and coach must find an optimal body position at take-off that allows them to increase the flight phase and therefore, the body rotation.

* For kick-start, the body rotation during the flight phase is mainly produced by an upward displacement of the front leg towards to the rear leg. Larger lower body displacement along the flight phase is recommended to obtain larger hip angle at water entry. This body position at water entry increase the counterclockwise rotation after the feet immersion which was related with a powerful dolphin-kick and a decrease in the loss of horizontal velocity under the water.

APPENDIX

1. Terminology and definitions of the most commonly spatiotemporal variables included in the analysis of the swimming start

Time 5 m (s)

- Starting signal--head cross the 5 m

  Arellano, Llana, Tella, Morales, and Mercade (2005); Arellano, Moreno, Martínez, and Oña (1996); Arellano, Pardillo, De La Fuente, and García (2000, 2002); Cuenca-Fernandez, Lopez-Contreras, and Arellano (2015); De la Fuente, García, and Arellano (2003); García-Ramos, Feriche, et al. (2015); García-Ramos, Padial, et al. (2015); Tor, Pease, and Ball (2015c); Welcher, Richard, Hinrichs, and George (2008) Benjanuvatra, Edmunds, and Blanksby (2007); Tor, Pease, and Ball (2015b)

- Starting signal--hip cross the 5 m

  Ayalon, Van Gheluwe, and Kanitz (1975); Welcher et al. (2008)

- Starting signal--toe cross the 5 m

  Takeda, Takagi, and Tsubakimoto (2012)

Time 7.5 m (s)

- Starting signal--head cross the 7.5 m

  Arellano et al. (2005); Arellano, Moreno, et al. (1996); Biel, Fischer, and Kibele (2010); De la Fuente et al. (2003); Tor et al. (2015c); Welcher et al. (2008), Tor et al. (2015b)

Time 10 m (s)

- Starting signal--head cross the 10 m

  Arellano et al. (2005); Arellano, Moreno, et al. (1996); Arellano et al. (2000, 2002); De la

Fuente et al. (2003); García-Ramos, Feriche, et al. (2015); García-Ramos, Padial, et al. (2015); McLean, Holthe, Vint, Beckett, and Hinrichs (2000); Tor et al. (2015b, 2015c)

- Starting signal--touch the timing plate at 10 m

  Beretić, Durović, and Okičić (2012)

Time 15 m (s)

- Starting signal--head cross the 15 m

  Arellano, Garcia, Gavilán, and Pardillo (1996); Benjanuvatra et al. (2007); Bishop et al. (2013); Cossor, Slawson, Justham, Conway, and West (2010); De la Fuente et al. (2003); García-Ramos, Feriche, et al. (2015); García-Ramos, Padial, et al. (2015); Issurin and Verbitsky (2002); Mason, Franco, Sacilotto, and Hazrati (2014); Ozeki, Sakurai, and Taguchi (2008); Ruschel et al. (2007); Seifert et al. (2010); Tor et al. (2015b, 2015c); Vantorre, Seifert, Bideau, et al. (2010); Vantorre et al. (2011); Vantorre, Seifert, Fernandes, VilasBoas, et al. (2010); West, Owen, Cunningham, Cook, and Kilduf (2011)

Reaction time (s)

- Starting signal--first sensible movement

  Benjanuvatra et al. (2007); Bezodis, Trewartha, and Salo (2008); Bloom (1978); Cossor et al. (2010); Disch, Hosler, and Bloom (1979); Elliot and Sinclair (1971); García-Ramos, Feriche, et al. (2015); Mason et al. (2007); Vilas-Boas et al. (2000); Honda, Sinclair, Mason, and Pease (2012); Slawinski et al. (2010); Slawson et al. (2012)

Movement time (s)

- First sensible movement--feet leave the block

  Barlow, Halaki, Stuelcken, and Greene (2014); Benjanuvatra et al. (2007); Blanksby, Nicholson, and Elliot (2002); Bloom (1978); Disch et al. (1979); Elliot and Sinclair (1971); García-Ramos, Feriche, et al. (2015); Slawinski et al. (2010); Vilas-Boas et al. (2000)

Take-off hands (s)

- Starting signal--hands leave the block

  Arellano et al. (2005); Arellano, Moreno, et al. (1996); De la Fuente et al. (2003); J. Miller, Hay, and Wilson (1984)

Rear foot take-off (%)

- Starting signal--rear foot leave the back plate

  Slawinski et al. (2010); Slawson et al. (2012); Takeda et al. (2012)

Block time (s)

- Starting signal--feet leave the block

  Alptekin (2014); Arellano, Garcia, et al. (1996); Arellano et al. (2005); Arellano, Moreno, et al. (1996); Arellano et al. (2000, 2002); Benjanuvatra et al. (2007); Beretić et al. (2012); Bezodis et al. (2008); Breed and Young (2003); Cossor et al. (2010); Cossor, Slawson, Shillabeer, Conway, and West (2011); Cuenca-Fernandez et al. (2015); De la Fuente et al. (2003); Garcia-Hermoso et al. (2013); Honda, Sinclair, Mason, and Pease (2010); Honda et al. (2012); Issurin and Verbitsky (2002); Kollias, Baltzopoulos, Chatzinikolaou, Tsirakos, and Vasiliadis (1990); Lee, Huang, Lin, and Lee (2002); J. Miller et al. (1984); Nomura, Takeda, and Takagi (2010); Ozeki, Sakurai, Taguchi, and Takise (2012); Ruschel et al. (2007); Seifert, Vantorre, and Chollet (2007); Seifert et al. (2010); Slawson et al. (2012); Slawson et al. (2011); Slawson et al. (2013); Takeda and Nomura (2006); Takeda et al. (2012); Thanopoulos et al. (2012); Tor et al. (2015c); Vantorre, Seifert, Bideau, et al. (2010); Vantorre, Seifert, Fernandes, VilasBoas, et al. (2010); Welcher et al. (2008)

- Reaction time + movement time

  Barlow et al. (2014); Blanksby et al. (2002); García-Ramos, Feriche, et al. (2015); Lee, Huang, and Lee (2012); Vilas-Boas et al. (2000)

- Starting signal--total vertical force fell to zero

  Mason et al. (2007); Mason et al. (2014); Tor et al. (2015b); (Tor et al., 2015c)

Horizontal position (m)

- Horizontal position of CoM from the front edge of the platform

  Nomura (2010); Slawinski et al. (2010)

Vertical position (m)

- Vertical position of CoM from the water surface

  Nomura (2010); Slawinski et al. (2010)

Horizontal displacement at take-off (m)

- Horizontal displacement from starting signal--feet leave the block

  Alptekin (2014); McLean et al. (2000); Vilas-Boas et al. (2000)

Vertical displacement at take-off (m)

- Vertical displacement from starting signal--feet leave the block

  Alptekin (2014)

Height take-off (m)

- Height of CoM at take-off

  Alptekin (2014); Holthe and McLean (2001); Kollias et al. (1990); McLean (2000)

Flight time (s)

- Feet leave the block--hands making contact with the water

  Alptekin (2014); Arellano, Garcia, et al. (1996); Arellano, Moreno, et al. (1996); Arellano et al. (2000, 2002); Beretić et al. (2012); Blanksby et al. (2002); Bloom (1978); Cuenca-

Fernandez et al. (2015); Detanico, Heidorn, Dal Pupo, Diefenthaeler, and dos Santos (2011); Disch et al. (1979); Jorgić et al. (2010); Kollias et al. (1990); Lee et al. (2012); J. Miller et al. (1984); Nomura et al. (2010); Seifert et al. (2010); Thanopoulos et al. (2012); Vantorre, Seifert, Bideau, et al. (2010); Vantorre, Seifert, Fernandes, VilasBoas, et al. (2010); Vilas-Boas et al. (2000)

- Feet leave the block--head making contact with the water

  Ruschel et al. (2007); Seifert et al. (2007); Tor et al. (2015b, 2015c)

Flight distance (m)

- Horizontal distance from feet leave the block--hands making contact with the water

  Alptekin (2014); Beretić et al. (2012); Blanksby et al. (2002); Breed and Young (2003); Cossor et al. (2010); Detanico et al. (2011); Galbraith, Scurr, Hencken, Wood, and Graham-Smith (2008); Holthe and McLean (2001); Jorgić et al. (2010); Kollias et al. (1990); McLean et al. (2000); Nomura et al. (2010); Ozeki et al. (2012); Seifert et al. (2010); Thanopoulos et al. (2012); Vilas-Boas et al. (2000)

- Horizontal distance from feet leave the block--CoM making contact with the water

  Takeda and Nomura (2006); Takeda et al. (2012)

- Horizontal distance from the front edge of the platform--head making contact with the water

  Mason et al. (2014); Ruschel et al. (2007); Tor et al. (2015b, 2015c)

Entry time (s)

- Starting signal--hands making contact with the water

  Alptekin (2014); Arellano, Garcia, et al. (1996); Arellano et al. (2005); Arellano et al. (2002); Bezodis et al. (2008); Breed and Young (2003); De la Fuente et al. (2003); J. Miller et al. (1984); Seifert et al. (2007); Vilas-Boas et al. (2000); Welcher et al. (2008)

- Hands making contact with the water--toe immersion

  Alptekin (2014); Seifert et al. (2010); Vantorre, Seifert, Fernandes, et al. (2010a, 2010b); Vilas-Boas et al. (2000)

- Block time + flight time

  Kollias et al. (1990)

Entry distance (m)

- Horizontal distance from front edge of the platform--hands making contact with the water

  Alptekin (2014); Chen and Tang (2005); Cuenca-Fernandez et al. (2015); Holthe and McLean (2001); Kollias et al. (1990); Seifert et al. (2010); Vilas-Boas et al. (2000)

- Horizontal distance from hands making contact with the water-- toe immersion

  A*rellano, Garcia, et al. (1996); Holthe and McLean (2001)*

- CoM making contact with the water--hands making contact with the water

  McLean et al. (2000)

Vertical displacement at entry (m)

- Vertical displacement from starting signal--hands making contact with the water

  Alptekin (2014)

Height entry (m)

- Height of CoM when hands making contact with the water

  Alptekin (2014); Holthe and McLean (2001); Kollias et al. (1990); McLean et al. (2000)

Relative height (m)

- Height of CoM at take-off − height of CoM when hands making contact with the water

  Alptekin (2014); McLean et al. (2000)

Entry hole (m)

- Distance between the forward and backward entry points of the body

  Mason et al. (2014); Tor et al. (2015b, 2015c)

Glide time (s)

- Toe immersion--beginning of the aquatic propulsion of the legs

  Vantorre, Seifert, Fernandes, et al. (2010a, 2010b)

- Hands making contact with the water--beginning of hand movement

  Miller et al. (1984); Seifert et al. (2007)

- Total start time (6.07 m) − time from start to full water entry

  Vilas-Boas et al. (2000)

Underwater time (s)

- Glide phase + underwater kicking--head cross the 15 m

  Vantorre, Seifert, Fernandes, VilasBoas, et al. (2010)

- Head making contact with the water--first arm stroke

  Ruschel et al. (2007); Seifert et al. (2007)

- Total immersion--breakout

  Tor et al. (2015b, 2015c)

Underwater distance (m)

- Horizontal distance from the hands making contact with the water--first arm stroke

  Ruschel et al. (2007)

- Horizontal distance from the hands making contact with the water--head break the water surface

  Arellano, Moreno, et al. (1996)

Maximum depth (m)

- Maximum depth reached by the head under the water surface

  Mason et al. (2014); Ruschel et al. (2007); Tor et al. (2015b, 2015c)

Time of full immersion (s)

- Starting signal--body is fully immersed

  Tor et al. (2015b, 2015c)

Horizontal distance of max depth (m)

- Horizontal distance from edge of the platform--maximum depth reached by the head

  Tor et al. (2015b, 2015c)

Time at max depth (s)

- Starting signal--head reaches maximum depth

  Tor et al. (2015b, 2015c)

Swim time (s)

- Head resurface--head cross the 15 m

  Seifert et al. (2007)

- First arm stroke--head cross the 15 m

  Vantorre, Seifert, Fernandes, VilasBoas, et al. (2010)

2. Terminology and definitions of the most commonly angular variables included in the analysis of the swimming start

Takeoff angle, dive angle or body orientation (°)

- Horizontal--hip--front edge of the platform

  Arellano, Garcia, et al. (1996); Arellano et al. (2005); Benjanuvatra et al. (2007); Breed and Young (2003); Galbraith et al. (2008)

- Horizontal--CoM--front edge of the platform

  Alptekin (2014); Arellano et al. (2000, 2002); Beretić et al. (2012); Cuenca-Fernandez et al. (2015); Jorgić et al. (2010); Nomura et al. (2010); Ozeki et al. (2012); Vantorre et al. (2011)

- Resultant velocity vector--horizontal axis

  Holthe and McLean (2001); McLean et al. (2000); Nomura et al. (2010); Takeda and Nomura (2006); Takeda et al. (2012)

- Arms--Trunk and body--horizontal axis

  Vantorre, Seifert, Bideau, et al. (2010)

- Vertical velocity vector--horizontal axis

  Mason et al. (2014); Tor et al. (2015b, 2015c)

- Trunk vector--horizontal axis

  McLean et al. (2000)

- Ankle--hip--horizontal axis

  Seifert et al. (2010)

Angle of attack (°)

- Resultant velocity vector--CoM--Hands

  Ozeki et al. (2008)

Knee angle (°)

- Hip--knee--ankle

  Beretić et al. (2012); Nomura et al. (2010); Slawinski et al. (2010); Slawson et al. (2012)

Ankle angle (°)

- Knee--ankle--finger toe

  Beretić et al. (2012); Nomura et al. (2010)

Hip angle (°)

- Ankle--hip--shoulder

  Seifert et al. (2010)

- Trunk line--leg line

  Arellano, Garcia, et al. (1996)

- Legs CoM--hip--shoulder

  Vantorre et al. (2011)

Shoulder angle or body angle (°)

- Hip--shoulder--wrist

  Seifert et al. (2010); Vantorre, Seifert, Bideau, et al. (2010)

- Arms CoM--hip--shoulder

  Vantorre et al. (2011)

Entry angle, attitude angle, body orientation or projection angle (°)

- Trunk vector--horizontal axis

  Detanico et al. (2011); McLean et al. (2000); Thanopoulos et al. (2012); Vantorre, Seifert, Bideau, et al. (2010); Vilas-Boas et al. (2000)

- CoM--hands--horizontal axis

  Alptekin (2014); Beretić et al. (2012); Cuenca-Fernandez et al. (2015); Jorgić et al. (2010); Ozeki et al. (2008); Ozeki et al. (2012)

- Trunk-- head--horizontal axis

  Ruschel et al. (2007)

- Wrist--hip--horizontal axis

  Arellano, Garcia, et al. (1996); Seifert et al. (2010)

- Fingertips--hip joint--horizontal axis

  Barlow et al. (2014)

- Horizontal and vertical velocity derived by integrating the acceleration

  Tor et al. (2015b, 2015c)

- Resultant velocity vector--horizontal axis

  Holthe and McLean (2001); McLean et al. (2000); Ozeki et al. (2008)

- Horizontal velocity vector--resultant velocity vector

  Bowers and Cavanagh (1975); Kollias et al. (1990)

- Vector velocity of CM--water surface 0.3 second before to the take-off

  Nomura et al. (2010)

- CoM of the body’s trajectory--horizontal and vertical velocity

  Mason et al. (2014)

3. Terminology and definition of the most commonly kinematic variables included in the analysis of the swimming start

Horizontal take-off velocity (m/s)

- Magnitude of horizontal velocity vector at the instant the swimmer leave the block

  Alptekin (2014); Arellano et al. (2000, 2002); Benjanuvatra, Lyttle, Blanksby, and Larkin (2004); Bezodis et al. (2008); Bowers and Cavanagh (1975); De la Fuente et al. (2003); Galbraith et al. (2008); Holthe and McLean (2001); Honda et al. (2010, 2012); Kollias et al. (1990); Lee et al. (2002); Nomura et al. (2010); Ozeki et al. (2012); Slawson et al. (2012); Slawson et al. (2011); Slawson et al. (2013); Takeda et al. (2012)

- The integral over time of the horizontal force expressed in body weight and multiplied by the gravitational constant

  Mason et al. (2007), Mason, 2014, Tor et al. (2015b, 2015c)

- Horizontal impulse ⁄ body mass

  Elliot and Sinclair (1971); García-Ramos, Feriche, et al. (2015); Vilas-Boas et al. (2000)

- Average horizontal velocity along the flight phase

  Thanopoulos et al. (2012); Welcher et al. (2008)

Vertical take-off velocity (m/s)

- Magnitude of vertical velocity vector at the instant the swimmer leave the block

  Alptekin (2014); Arellano et al. (2005); Arellano et al. (2000, 2002); Benjanuvatra et al. (2004); Bowers and Cavanagh (1975); De la Fuente et al. (2003); Galbraith et al. (2008); Holthe and McLean (2001); Kollias et al. (1990); Lee et al. (2002); Nomura et al. (2010); Slawinski et al. (2010); Takeda et al. (2012)

- The integral over time of the vertical force expressed in body weight and multiplied by the gravitational constant

  Mason et al. (2007), Mason, 2014, Tor et al. (2015b, 2015c)

- Vertical impulse ⁄ body mass

  Elliot and Sinclair (1971); García-Ramos, Feriche, et al. (2015); Vilas-Boas et al. (2000)

Resultant take-off velocity (m/s)

- Magnitude of resultant velocity vector at the instant the swimmer leave the block

  Arellano et al. (2005); Arellano et al. (2000, 2002); Benjanuvatra et al. (2007); Benjanuvatra et al. (2004); Breed and Young (2003); Holthe and McLean (2001); Jorgić et al. (2010); McLean et al. (2000); Nomura et al. (2010); Ozeki et al. (2012); Slawinski et al. (2010); Takeda and Nomura (2006); Takeda et al. (2012)

- Resultant impulse ⁄ body mass

  García-Ramos, Feriche, et al. (2015)

Average horizontal acceleration (m/s^2)

- Average horizontal force on the block ⁄ body mass

  García-Ramos, Feriche, et al. (2015)

- Rate of change in horizontal velocity over the block time

  Tor et al. (2015b, 2015c)

- Mean horizontal acceleration of CoM during 0.3 second just before the take-off

  Nomura et al. (2010)

Average vertical acceleration (m/s^2)

- Average vertical force on the block ⁄ body mass

  García-Ramos, Feriche, et al. (2015)

- Mean vertical acceleration of CoM during 0.3 second just before the take-off

  Nomura et al. (2010)

Peak horizontal acceleration (m/s^2)

- Peak horizontal force on the block ∕ body mass

  García-Ramos, Feriche, et al. (2015)

Peak vertical acceleration (m/s^2)

- Peak vertical force on the block ∕ body mass

  García-Ramos, Feriche, et al. (2015)

Angular momentum (Kg.m^2/s)

- Angular momentum at the instant the swimmer leave the block

  McLean et al. (2000); Vantorre, Seifert, Bideau, et al. (2010); Vantorre et al. (2011)

Mean standard deviation for the angular momentum (Kg.m^2/s)

- Mean standard deviation for the angular momentum at the instant the swimmer leave the block

  Vantorre, Seifert, Bideau, et al. (2010); Vantorre et al. (2011)

Maximum change in momentum of inertia (Kg.m^2)

- Maximum momentum of inertia − minimum values obtained along the flight phase

  McLean et al. (2000)

Mean angular velocity knee (rad/s)

- Knee’s angular difference between maximum extension and maximum flexion ⁄ time spent

  Cuenca-Fernandez et al. (2015)

Horizontal velocity at hands entry (m/s)

- Magnitude of horizontal velocity at the instant of the hands make contact with the water

  Alptekin (2014); Arellano et al. (2002); Bowers and Cavanagh (1975); Lee et al. (2002); McLean et al. (2000); Seifert et al. (2010); Tor et al. (2015b, 2015c); Vilas-Boas et al. (2000)

Vertical velocity at hands entry (m/s)

- Magnitude of vertical velocity at the instant of the hands make contact with the water

  Alptekin (2014); Arellano et al. (2002); Bowers and Cavanagh (1975); Lee et al. (2002); Seifert et al. (2010); Vilas-Boas et al. (2000)

Resultant velocity at hands entry (m/s)

- Magnitude of resultant velocity at the instant of the hands make contact with the water

  Arellano et al. (2002); Seifert et al. (2010); Tor et al. (2015c)

Underwater velocity (m/s)

- Average velocity between head entry--first arm stroke

  Ruschel et al. (2007)

- Underwater horizontal distance ⁄ time spent under the water

  Tor et al. (2015b, 2015c)

Mean velocity 0-5 m (m/s)

- Distance ⁄ time between the starting signal and the head crosses the 5 m

  Arellano et al. (2005); Arellano et al. (2002); De la Fuente et al. (2003); Tor et al. (2015b, 2015c)

Mean velocity 5-7.5 m (m/s)

- Distance ⁄ time between the head crosses the 5 m and the 7.5 m

  Arellano et al. (2005); Honda et al. (2010, 2012); Tor et al. (2015b, 2015c)

Mean velocity 7.5-10 m (m/s)

- Distance ⁄ time between the head crosses the 7.5 m and the 10 m

  Arellano et al. (2005); Tor et al. (2015b, 2015c)

Mean velocity 10-15 m (m/s)

- Distance ⁄ time between the head crosses the 10 m and the 15 m

  Tor et al. (2015b, 2015c)

4. Terminology and definitions of the most commonly kinetic variables included in the analysis of the swimming start

Average horizontal force (N)

- Average force developed by the swimmers in the horizontal direction on the block

  Chen and Tang (2005); Cossor et al. (2010); De la Fuente et al. (2003); García-Ramos, Feriche, et al. (2015); Lee, Huang, Wang, and Lin (2001); Naemi, Reza, Ahadian, and Barjasteh (2001)

- Horizontal impulse on the block/movement time

  Benjanuvatra et al. (2004); García-Ramos, Feriche, et al. (2015); Honda et al. (2010, 2012)

Average vertical force (N)

- Average force developed by the swimmers in the vertical direction on the block

  Chen and Tang (2005); Cossor et al. (2010); De la Fuente et al. (2003); Lee et al. (2001); Naemi et al. (2001)

- Vertical impulse on the block/movement time

  Benjanuvatra et al. (2004); García-Ramos, Feriche, et al. (2015)

Peak horizontal force (BW) or (N)

- Maximum force produced in the horizontal direction by the swimmers at instant to leave the block

  Arellano et al. (2005); Arellano et al. (2000, 2002); Benjanuvatra et al. (2004); Bishop et al. (2013); Cossor et al. (2011); Cousin and Dyson (2004); Galbraith et al. (2008); García-Ramos, Feriche, et al. (2015); Lee et al. (2002); Slawson et al. (2012); Slawson et al. (2011); Slawson et al. (2013); Tor et al. (2015b, 2015c)

- Maximum force produced in the horizontal direction by the swimmers at instant of the rear foot leaves the block

    Benjanuvatra et al. (2004); Honda et al. (2012); Slawson et al. (2012); Slawson et al. (2011); Slawson et al. (2013)

Peak vertical force (BW) or (N)

- Maximum force produced in the vertical direction by the swimmers at instant to leave the block

    Arellano et al. (2005); Arellano et al. (2000, 2002); Benjanuvatra et al. (2004); Bishop et al. (2013); Cossor et al. (2011); Cousin and Dyson (2004); Galbraith et al. (2008); García-Ramos, Feriche, et al. (2015); Lee et al. (2002); Slawson et al. (2012); Slawson et al. (2011); Slawson et al. (2013); Tor et al. (2015b, 2015c)

- Maximum force produced in the vertical direction by the swimmers at instant of the rear foot leaves the block

    Honda et al. (2012); Slawson et al. (2012); Slawson et al. (2011); Slawson et al. (2013)

Resultant peak force (BW) or (N)

- Maximum force produced in the resultant direction by the swimmers at instant to leave the block

    Chen and Tang (2005); Elliot and Sinclair (1971); Honda et al. (2012); Mason et al. (2014); Tor et al. (2015b, 2015c)

Peak vertical grab force (BW) or (N)

- Maximum force produced by the hands at the instant of the swimmer’s hands leave the block

    Honda et al. (2012); Mason et al. (2014); Tor et al. (2015b, 2015c)

Average power on the block (W/kg of BW)

- The instantaneous product of resultant force by resultant velocity instant by instant

  Bezodis et al. (2008); Mason et al. (2007); Mason et al. (2014); Tor et al. (2015b, 2015c)

Peak power per kilogram (w/kg)

- Instantaneous horizontal force × instantaneous horizontal velocity on the block

  Tor et al. (2015c); Mason et al. (2007)

Work on the block (J/kg BM)

- Integral of power over time

  Mason et al. (2007)

Horizontal impulse (N.s)

- Horizontal force × impulse time

  Benjanuvatra et al. (2007); Benjanuvatra et al. (2004); Breed and Young (2003); Galbraith et al. (2008); García-Ramos, Feriche, et al. (2015); Vantorre et al. (2011); Vilas-Boas et al. (2000)

Vertical impulse (N.s)

- Vertical force × impulse time

  Benjanuvatra et al. (2007); Benjanuvatra et al. (2004); Breed and Young (2003); García-Ramos, Feriche, et al. (2015); Vantorre et al. (2011); Vilas-Boas et al. (2000)

Resultant impulse (N.s)

- Resultant force × impulse time

  Slawinski et al. (2010); Vilas-Boas et al. (2000)

Rate of force development on the block (N/s)

- Slope of the first peak acceleration × body mass

  Slawinski et al. (2010)

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RESUMEN

R.1. RESUMEN (Correspondiente a Thesis Scope)

La salida es el primer elemento técnico de una prueba de natación; permite a los nadadores entrar en el agua más rápido que la velocidad media de nado y a pesar de que es la fase más corta y más rápida, una salida efectiva es esencial para el éxito de una prueba de natación.

A lo largo de la historia los nadadores han utilizado diversas técnicas de salida. Hoy en día la más popular es la salida de atletismo con apoyo posterior debido a las grandes ventajas que proporciona frente a técnicas anteriores. Esta salida está caracterizada por una posición asimétrica de los pies en el poyete. En ella un pie se coloca adelantado en el borde anterior del poyete mientras que el otro pie se coloca sobre una superficie estable ubicada en el borde posterior del poyete. Esta superficie llamada comúnmente apoyo posterior puede desplazarse en diferentes posiciones dependiendo de las preferencias de los nadadores aumentando su estabilidad en el momento de la salida y permitiéndoles desarrollar mayores niveles de fuerza.

En el estudio biomecánico de las salidas de natación han sido muchas las variables que se han incluido con el objetivo de determinar las ventajas o características que debe tener una determinada técnica para mejorar el rendimiento total de las pruebas de natación. Entre todas estas variables, el momento angular es considerado un factor importante para el óptimo rendimiento de las salidas debido a su influencia sobre la posición del cuerpo de los nadadores en el instante de la entrada en el agua y por lo tanto sobre el rendimiento sobre la posterior fase subacuática. A pesar de su relevancia, son muy pocos los estudios que incluyen resultados del momento angular y ninguno el que evaluó el desarrollo del momento angular durante la fase de poyete, la fase de vuelo y la fase de deslizamiento en una salida de natación. Por este motivo, el principal objetivo de esta tesis es estudiar el rendimiento de la salida de atletismo con apoyo posterior centrándonos principalmente en las ventajas que el momento angular y la rotación del cuerpo proporciona a esta salida.

La tesis que se presenta se divide en diferentes partes. En primer lugar se desarrolla una introducción general donde se resume la historia, evolución y relevancia de las salidas de natación y donde se realiza una breve descripción de las bases teóricas del momento angular. A continuación la tesis se divide en dos capítulos. El objetivo general del Capítulo 1 es determinar las claves para la mejora de la salida de atletismo con apoyo posterior. El Capítulo 2 se centra en el análisis biomecánico del desarrollo del momento angular alrededor del eje transversal del cuerpo desde la señal de salida hasta la fase de deslizamiento de la salida de atletismo con apoyo posterior.

Cada uno de estos capítulos fue dividido en dos secciones. La sección 1.I (Capítulo 1) está centrada en el análisis de las ventajas que la salida de atletismo con apoyo posterior proporciona en el poyete y fase de vuelo en comparación con la salida de agarre. En este capítulo se demuestra que la principal ventaja de la salida de atletismo con apoyo posterior radica en el incremento del desarrollo de fuerza en el poyete en un periodo de tiempo más corto. En esta sección también se incluye una evaluación de la relación entre las variables involucradas en la fase de poyete y fase de vuelo con el objetivo de determinar las formas de mejorar el rendimiento de la salida de atletismo con apoyo posterior. Fue concluido que tiempos de vuelo más largos y un menor desplazamiento de la pierna atrasada durante la fase de poyete incrementa la rotación del cuerpo durante la fase de vuelo. Como consecuencia, el descenso de la velocidad horizontal producido en la entrada en el agua se reduce dando lugar a un mejor rendimiento de la salida de atletismo con apoyo posterior.

Posteriormente, en la sección 1.II (Capítulo 2) se realiza una comparación de la mecánica de rotación en el poyete y durante la fase de vuelo entre la salida de atletismo con apoyo posterior y la salida de agarre. Este estudió reveló que la principal rotación producida durante la fase de vuelo de la salida de atletismo con apoyo posterior es consecuencia del desplazamiento de la pierna adelantada la cual realiza un movimiento ascendente para juntarse con la pierna atrasada. Por el contrario, en la salida de agarre la rotación del cuerpo es principalmente desarrollada por un desplazamiento descendente del tronco. Fue concluido que aunque ambas estrategias de rotación proporcionan un rendimiento similar en la entrada en el agua, las ventajas temporales que la salida de atletismo con apoyo posterior obtiene en el poyete la hacen una salida superior.

El momento angular es una de las variables más importantes en el rendimiento de las salidas. El impulso angular desarrollado en el poyete determina la cantidad de rotación del cuerpo que se realiza durante la fase de vuelo. En la sección 2.I (chapter 2) fue determinado que un incremento del momento angular depende del ángulo de la rodilla en la posición de salida. Un ángulo de aproximadamente 140° y un ángulo de los hombros de 80° durante toda la fase de poyete ha sido relacionado con un incremento del momento angular desarrollado durante la fase de poyete y por lo tanto con un mejor rendimiento de la salida de atletismo con apoyo posterior.

Además de un momento angular mayor, una mayor fase de vuelo es necesaria para desarrollar una mayor rotación del cuerpo permitiendo a su vez un mayor descenso de los valores de momento angular después de la entrada de los pies en el agua. La sección 2.II (capítulo 2) indicó que mayores valores negativos de momento angular después de la entrada de los pies en el agua están relacionados con la ejecución de una patada subacuática lo cual reduce la pérdida de velocidad horizontal durante la fase de deslizamiento de la salida de atletismo con apoyo posterior.

Para finalizar la tesis se incluye una sección de las conclusiones generales así como las limitaciones y futuros estudios y las aplicaciones prácticas extraídas de los principales resultados de esta tesis.

R.2. Introducción (Correspondiente a General Introducción)

LAS SALIDAS DE NATACIÓN

El rendimiento de la salida de natación es cuantitativamente medido por el tiempo que transcurre desde que se da la señal de salida y hasta que la cabeza de los nadadores cruzan la línea imaginaria de los 10 m (Arellano, Brown, Cappaert, & Nelson, 1994) o los 15 m (Cossor & Mason, 2001; Issurin & Verbitsky, 2002) o los 15 m.

El tiempo invertido en una salida de natación representa aproximadamente el 0.8-21.6% del tiempo total de una prueba de natación, siendo este porcentaje menor cuanto más larga es la prueba (Mason & Cossor, 2000). Sin embargo y a pesar de su relativamente pequeña contribución al rendimiento total de una prueba, una óptima ejecución de la salida es esencial para obtener un buen rendimiento total, especialmente en pruebas cortas. Previamente ha sido demostrado que una mejora de la salida puede suponer una reducción mínima de 0.10 s sobre el tiempo total de una prueba (Maglischo, 2003). En este sentido y teniendo en cuenta que a menudo la diferencia de rendimiento entre los nadadores suele estar determinado por 0.01 s, una salida efectiva puede suponer el éxito o el fracaso de la prueba. Así mismo, en diferentes análisis de la competición realizados a lo largo de los años se ha determinado que un menor tiempo de salida supone un menor tiempo total de la prueba tanto en distancias cortas (50-100 m) como en distancias más largas (800-1500 m) (Arellano et al., 1994; Arellano et al., 2001; Mason & Cossor, 2000; Mason et al., 1998; Thompson, Haljand, & MacLaren, 2006).

Debido a la influencia de las salidas en el rendimiento total de las pruebas de natación, a lo largo de los años se han ido desarrollando diferentes técnicas con el objetivo de encontrar aquella que mayores ventajas proporcionase a los nadadores. Una de las técnicas más populares fue la salida de agarre, utilizada en competiciones internacionales desde el 1972 hasta el 2009. En esta salida los nadadores colocaban sus pies en una posición paralela en el borde anterior del poyete con una separación similar a la del ancho de los hombros. Las rodillas y caderas estaban flexionadas de tal forma que las manos pudiesen agarrarse al borde anterior del poyete.

Otra de las técnicas más utilizadas por los nadadores en competición fue la salida de atletismo desarrollada en 1973. La principal característica de esta técnica es la posición asimétrica de los pies en el poyete de salida, en la cual un pie se coloca en la parte anterior del poyete mientras que el otro se coloca en la parte posterior. Al igual que en la salida de agarre, las rodillas y caderas están flexionadas de tal forma que permita a la manos agarrarse al borde frontal del poyete.

A pesar de las diferencias visibles entre la salida de agarre y la salida de atletismo, los resultados de los diferentes estudios biomecánicos realizados para determinar las ventajas de una sobre la otra fueron contradictorios (Ayalon, Van Gheluwe, & Kanitz, 1975; Blanksby, Nicholson, & Elliot, 2002; Counsilman, Counsilman, Nomura, & Endo, 1986; Holthe & McLean, 2001; Issurin & Verbitsky, 2002; Jorgić et al., 2010; Krüger, Wick, Hohmann, El-Bahrawi, & Koth, 2003; Mason, Alcock, & Fowlie, 2007; Thanopoulos et al., 2012; Vantorre, Seifert, Fernandes, Vilas-Boas, & Chollet, 2010; Zatsiorsky, Bulgakova, & Chaplinsky, 1979) lo que dio lugar a que ambas técnicas coexistiesen durante más de cuarenta años.

En 2009, la aprobación por parte de la Federación Internacional de Natación (FINA) (FR.2.7. Starting platforms en la normativa de la FINA) del uso de un nuevo poyete de salida dió lugar a la aparición de una nueva técnica, la salida de atletismo con apoyo posterior. Estos nuevos poyetes de salida están provistos de un soporte colocado en la parte posterior del poyete que permite a los nadadores adoptar la misma posición que en la salida de atletismo añadiendo un apoyo para el pie atrasado. Además, este soporte puede colocarse en cinco posiciones diferentes en función de sus preferencias.

Como consecuencia de esta modificación en los poyetes de salida, diversos estudios biomecánicos demostraron que con esta nueva técnica los nadadores eran capaces de incrementar los niveles de fuerza desarrollados en el poyete observando mayores picos de fuerza vertical y horizontal, una mayor fuerza horizontal media y una mayor aceleración y velocidad tanto horizontal como vertical en el momento del despegue del poyete respecto a la salida de atletismo (Biel, Fischer, & Kibele, 2010; Honda, Sinclair, Mason, & Pease, 2010; Ozeki, Sakurai, Taguchi, & Takise, 2012). Además, fue demostrado que este soporte permite desarrollar mayores niveles de fuerza explosiva, lo cual incrementa la velocidad horizontal obtenida en el momento del despegue sin que esto suponga un aumento del tiempo que los nadadores están sobre el poyete (Biel et al., 2010; Honda et al., 2010; Ozeki et al., 2012; Slawinski et al., 2010). Estos mayores valores de velocidad horizontal obtenidos en el despegue del poyete permite a los nadadores recorrer mayores distancias durante la fase de vuelo en un tiempo más corto respecto a la salida de atletismo (Beretić, Durović, & Okičić, 2012; Nomura, Takeda, & Takagi, 2010; Ozeki et al., 2012) lo cual finalmente da lugar a grandes ventajas en el tiempo a los 5, 7.5, 10 y 15 m (Beretić et al., 2012; Biel et al., 2010; Honda et al., 2010; Ozeki et al., 2012).

Para una óptima evaluación biomecánica de las salidas de natación, éstas son comúnmente divididas en: fase de poyete (tiempo entre la señal de salida y el instante donde los pies del nadadores dejan el poyete), fase de vuelo (lapso de tiempo entre que los pies de los nadadores abandonan el poyete y el primer contacto con las manos), fase acuática (tiempo entre el primer contacto de los nadadores con el agua y el instante donde comienza la primera patada y/o brazada) y fase de nado (lapso de tiempo entre el comienzo de la primera patada y/o brazada y el instante donde la cabeza del nadador alcanza la línea imaginaria de los 15 m) (Elipot et al., 2009; Guimaraes & Hay, 1985; Tor, Pease, & Ball, 2014). El porcentaje de contribución de cada una de las fases al rendimiento total de la salida fue establecido en un 11%, 5%, 56% y 28% respectivamente (Tor et al., 2014). Dentro de cada fase diversas variables espaciotemporales (p. ej. tiempo de poyete, tiempo de vuelo o tiempo a 5 m), angulares (p. ej. ángulo de orientación del cuerpo, ángulo de entrada, ángulo de la rodilla o ángulo de la cadera), cinematicas (p. ej. velocidad horizontal de despegue, momento angular o aceleración horizontal media) o cinéticas (p. ej. fuerza horizontal o impulso horizontal) son utilizadas para su evaluación biomecánica.

Los métodos empleados para la adquisición de los resultados cuantitativos de cada una de las variables son la cinematografía o el uso de plataformas de fuerzas. La cinematografía permite obtener variables espaciotemporales, angulares y cinemáticas. Este método consiste en la grabación y posterior análisis de los vídeos de las técnicas ejecutadas. El uso de plataforma de fuerza es comúnmente utilizado par la obtención de las variables cinéticas sin embargo, este método también permite la adquisición de variables temporales y cinemáticas.

EL MOMENTO ANGULAR

El momento angular es un factor mecánico que permite a los deportistas rotar. Está determinado por el momento de inercia (habilidad de un cuerpo para resistirse a la rotación en un determinado eje) y por la velocidad angular (desplazamiento angular en un determinado espacio de tiempo).

$$H\ (\mathrm{kg.m^2/s}) = I\ (\mathrm{kg/m^2})\ \mathrm{x}\ \omega\ (\mathrm{radians/s}) \qquad (\mathrm{R.1})$$

La cantidad de momento angular depende del torque o momento de fuerza generado por los deportistas y del tiempo de aplicación de dicho torque. A su vez, el torque es el producto de una fuerza externa que actúa sobre un cuerpo y la distancia perpendicular desde el centro de masas (CM) hasta la línea de acción de la fuerza. En este sentido, el deportista obtendrá momento angular mientras éste esté en contacto con una superficie a través de las fuerza que los segmentos corporales generan contra la misma.

En el momento en el que los deportistas no estén en contacto con una superficie que les permita aplicar fuerza la cantidad de momento angular estará determinada y permanecerá constante (principio de conservación del momento angular). En este sentido y en base a la cantidad de momento angular que los deportistas hayan obtenido en contacto con la superficie, éstos podrán cambiar su posición corporal mediante un incremento del momento de inercia (alejando los segmentos corporales del CM) o un incremento de la velocidad angular (aproximando los segmentos corporales al CM).

El momento angular es considerado una variable importante en las salidas de natación debido a la influencia de esta variable sobre la posición corporal de los nadadores en la entrada en el agua. El impulso angular desarrollado por los nadadores en la fase de poyete va a permitirles desarrollar diferentes movimientos rotacionales durante la fase de vuelo y variar la posición del cuerpo en la entrada en el agua.

Estudios previos que analizaron diferentes técnicas de salida demostraron que mayores valores de momento angular en el momento del despegue conducen a una entrada en el agua más vertical. Por el contrario, un menor momento angular en el momento del despegue fue relacionado con una entrada en el agua más plana (McLean, Holthe, Vint, Beckett, & Hinrichs, 2000; Vantorre et al., 2010; Vantorre et al., 2011).

R.3. Ventajas biomecánicas de la salida de atletismo con apoyo posterior durante la fase aérea (correspondiente al Capítulo 1)

Tras la aparición de los nuevos poyetes con apoyo posterior, numerosos estudios han sido realizados con el objetivo de determinar las ventajas del uso de la nueva salida de atletismo con apoyo posterior respecto a técnicas anteriores como la salida de atletismo convencional y la salida de agarre. Todos estos estudios han demostrado una clara superioridad de la salida de atletismo con apoyo posterior en cuanto a la velocidad horizontal de despegue, el tiempo de poyete, el tiempo de vuelo y el tiempo a los 5, 7.5, 10 y 15 m (Beretić et al., 2012; Biel et al., 2010; Honda, Sinclair, Mason, & Pease, 2012; Nomura et al., 2010; Ozeki et al., 2012). Sin embargo, es importante recalcar que la mayoría de estos estudios compararon la salida de atletismo con apoyo posterior y la salida de atletismo convencional. Hasta el momento solamente en una ocasión fueron analizadas las diferencias entre la salida de atletismo con apoyo posterior y la salida de agarre en cuanto a la velocidad horizontal de despegue, tiempo de poyete y tiempo a 7.5 m (Biel et al., 2010).

Por otra parte, muchos de los estudios biomecánicos que analizaron la salida de atletismo con apoyo posterior se centraron en el análisis de la fase de poyete. Sin embargo, ningún estudio incluyó un análisis completo de la fase de poyete y fase de vuelo de la salida de esta salida ni resultados del momento angular o la rotación del cuerpo generado durante esta técnica de salida.

En este sentido, dos estudios fueron conducidos con el objetivo de analizar la ventajas durante la fase de poyete y la fase de vuelo de la salida de atletismo con apoyo posterior incluyendo un análisis de las variables rotacionales y una comparación con la salida de agarre.

R.3.1. Determinación de las ventajas biomecánicas y de la relación entre las variables involucradas en la fase aérea de la salida de atletismo con apoyo posterior (correspondiente al capítulo 1, sección 1.I)

El propósito de este estudio fue determinar las diferencias biomecánicas entre la salida de atletismo con apoyo posterior y la salida de agarre con el objetivo de definir las claves del mejor rendimiento de la salida de atletismo con apoyo posterior. Con este propósito dieciséis nadadores del equipo nacional de natación fueron analizados (70.7 ± 8.2 kg; 178.7 ± 9.7 cm; 24.9 ± 4.3 años; 766.95 ± 124.4 puntos FINA). Cuatro cámaras de alta definición fueron utilizadas para grabar la fase de poyete y fase de vuelo de cada salida y una cámara subacuática fue utilizada para determinar el tiempo a 5 m. Una estructura de calibración con treinta y cuatro puntos control fue colocada previamente a la filmación de las salidas para la posterior adquisición de las variables cuantitativas. Las coordenadas fueron reconstruidas mediante un método 3D DLT. La fiabilidad de dichas coordenadas fue menor de 0.82 cm. Para la determinación del CM, 21 puntos antropométricos fueron digitalizados manualmente empleando el programa Kwon 3D XP.

A partir de este estudio ha sido demostrado que la principal ventaja de la salida de atletismo con apoyo posterior con respecto a la salida de agarre radica en la capacidad de ésta para desarrollar una aceleración mayor un tiempo muy corto (previamente al despegue del pie atrasado). Esta ventaja permite un rápido incremento de la velocidad horizontal a lo largo de la fase de poyete de tal forma que con la salida de atletismo con apoyo posterior los nadadores son capaces de en un tiempo más corto obtener una velocidad horizontal en el momento del despegue similar a la desarrollada con la salida de agarre (Figura R.3.1.1).

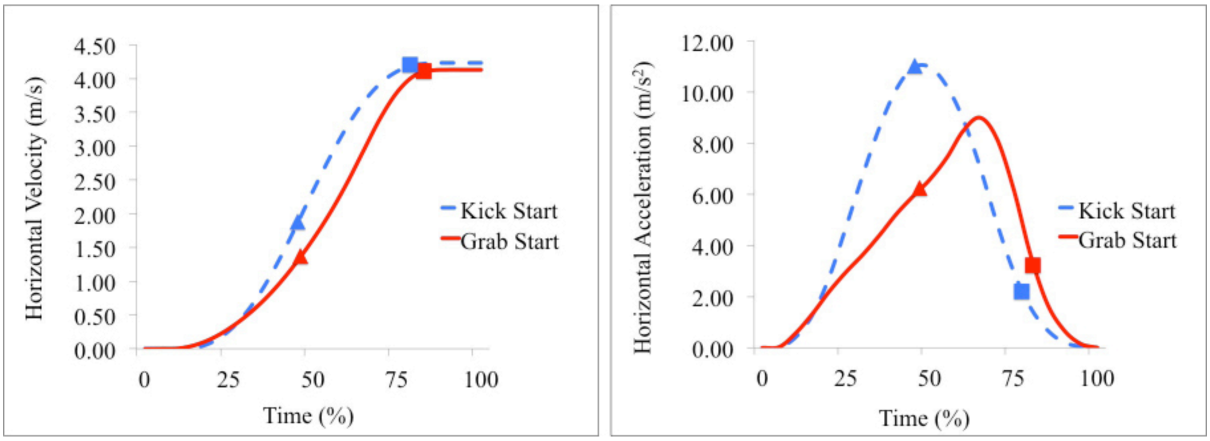

Figura R3.1.1. Curva de la velocidad horziontal del CM-tiempo y curva de la aceleración horizontal del CM-tiempo con valores estandarizados en la salida de agarre y la salida de atletismo con apoyo posterior. Cada curva fue dividida en dos fases: despegue de manos (triángulo azul) y despegue del poyete (cuadrado azul) para la salida de atletismo con apoyo posterior y despegue de manos (triángulo rojo) y despegue del poyete (cuadrado rojo) para la salida de agarre.

Otra de las ventajas observadas de la salida de atletismo con apoyo posterior respecto a la salida de agarre ha sido la posición del cuerpo en el momento del despegue del poyete. En este instante el cuerpo de los nadadores en la salida de atletismo con apoyo posterior está dirigido hacia delante y hacia abajo. Por el contrario, en la salida de agarre la dirección del cuerpo es hacia delante y hacia arriba (Figure R3.1.2). Una posición más baja del cuerpo en el instante del despegue limita la rotación durante la fase de vuelo en la salida de atletismo con apoyo posterior, sin embargo también le permite a los nadadores obtener un ángulo de orientación del cuerpo significativamente mayor que el de la salida de agarre y por lo tanto una menor pérdida de velocidad horizontal en la entrada en el agua.

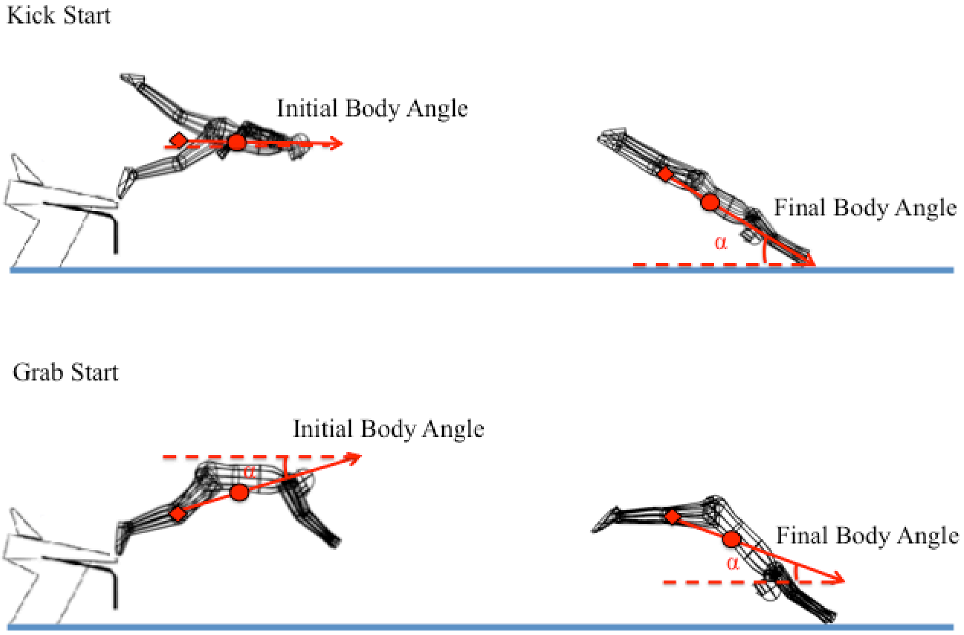

Figura R3.1.2. Diferencias de la orientación del cuerpo producidas para la salida de agarre con apoyo posterior y la salida de agarre (formado por el CM de las piernas y el CM del cuerpo) siguiendo la dirección del movimiento durante el despegue y la entrada de las manos en el agua.

Por otra parte, el coeficiente de correlación de Pearson reveló que una mejora de la salida de atletismo con apoyo posterior depende de la capacidad para desarrollar una mayor aceleración en un tiempo más corto. Además, el desplazamiento de la pierna atrasada fue observado un factor relevante para el mejor rendimiento de esta salida debido a su relación con el ángulo de despegue y el tiempo de vuelo. En este sentido, un excesivo desplazamiento de la pierna atrasada va a incrementar el ángulo de despegue y por lo tanto reducir el tiempo de la fase de vuelo. Como consecuencia la rotación del cuerpo se reducirá dando lugar a un ángulo de orientación menor que provocaría un incremento de la pérdida de velocidad horizontal durante la entrada en el agua y un mayor tiempo a 5 m.

R3.2. Análisis de la mecánica de rotación en el rendimiento de la salida de natación (correspondiente al capítulo 1, sección 1.II)

El propósito de este estudio fue analizar la mecánica de rotación para la salida de atletismo con apoyo posterior y la salida de agarre a lo largo de la fase de vuelo con el objetivo de entender la contribución del momento angular en la rotación del cuerpo y las diferencias que se producen entre las técnicas simétricas y asimétricas. Con este objetivo 9 nadadores de élite pertenecientes a la selección nacional de natación fueron analizados (70.0 ± 7.7 kg; altura 178 ± 9.4 cm; edad 24.5 ± 5.3; 824 ± 119 puntos FINA).

Cuatro cámaras de alta definición fueron utilizadas para grabar la fase de poyete y fase de vuelo de cada salida y una cámara subacuática fue utilizada para determinar el tiempo a 5 m. Una estructura de calibración con treinta y cuatro puntos control fue colocada previamente a la filmación de las salidas para la posterior adquisición de las variables cuantitativas. Las coordenadas fueron reconstruidas mediante un método 3D DLT. La fiabilidad de las coordinadas fue menor de 0.78 cm. Para la determinación del CM, 21 puntos antropométricos fueron digitalizados manualmente empleando el programa Kwon 3D XP.

Diferentes movimientos rotacionales han sido mostradas por el momento angular y las variables angulares analizadas en este estudio. Las diferentes posiciones de salida que los nadadores adoptan durante la salida de atletismo con apoyo posterior (posición asimétrica) y durante la salida de agarre (posición simétrica) dan lugar a diferencias en la rotación del cuerpo producida durante la fase de vuelo de la salida.

En la salida de atletismo con apoyo posterior, la curva del momento angular de la pierna atrasada demostró un desplazamiento ascendente de ésta durante la fase de poyete, lo que da lugar a una posición de despegue asimétrica, con una mayor altura de la pierna atrasada respecto a la pierna adelantada. Debido a esta posición de despegue, durante la fase de vuelo la pierna adelantada produce un movimiento ascendente de forma que se aproxima a la pierna atrasada para poder entrar en el agua con ambas piernas juntas. Como consecuencia, los nadadores fueron capaces de alcanzar el agua con una posición de las piernas más alta respecto al tronco que la observada durante la salida de agarre.

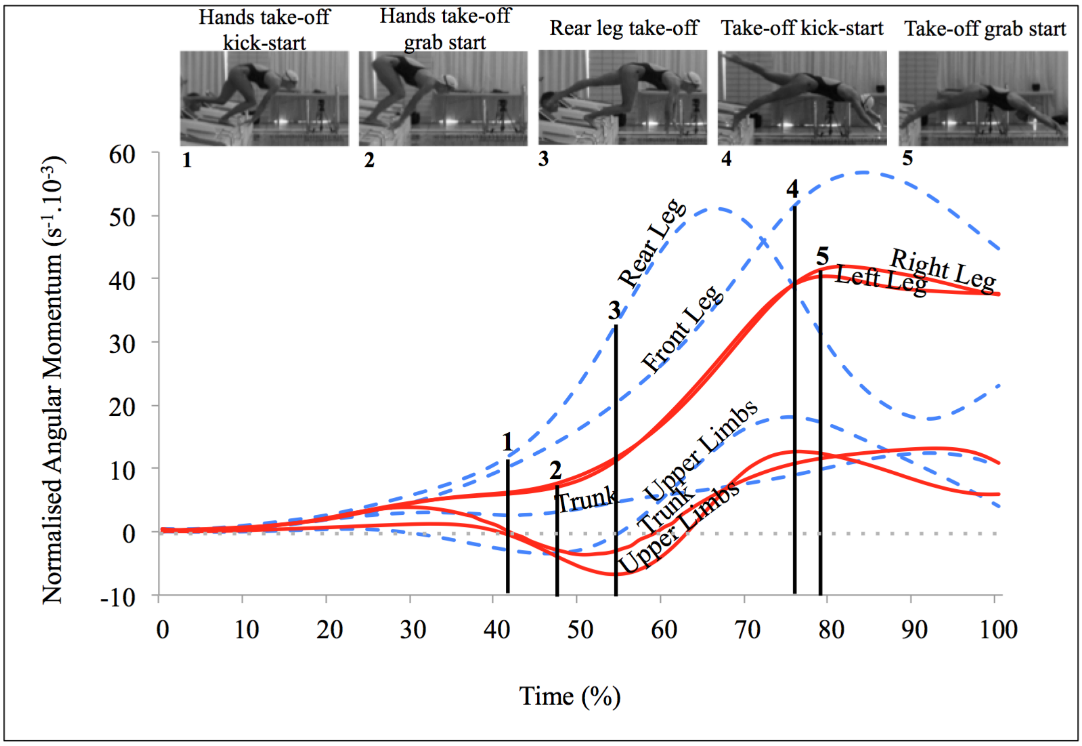

Figure 1II.2. Diferencias en el momento angular normalizado para cada segmento corporal para la salida de agarre y la salida de atletismo con valores estandarizados (líneas azules corresponden con la salida de atletismo con apoyo posterior y las líneas rojas con la salida de agarre).

Por el contrario, la posición simétrica de la salida de agarre no permite un desplazamiento de los miembros inferiores durante la fase de poyete, por lo que los nadadores despegan con ambas piernas juntas. Esta característica dificulta el desplazamiento de los miembros inferiores durante la fase de vuelo de tal forma que los valores del momento angular de ambas piernas fueron mantenidas prácticamente constantes. En la salida de agarre una mayor rotación del tronco parece ser la clave de una óptima entrada en el agua. Los valores significativamente más altos del momento angular del tronco obtenidos en el momento del despegue en esta técnica con respecto a la salida de atletismo con apoyo posterior indicaron una mayor rotación de este segmento a lo largo de la fase de vuelo con el objetivo de entrar en el agua en una posición más hidrodinámica.

A pesar de las diferentes estrategias de rotación, los resultados de las variables temporales parecen indicar que ambas salidas obtienen un rendimiento similar en la entrada en el agua. Sin embargo, las ventajas temporales que la salida de atletismo con apoyo posterior obtiene en el poyete la hacen una salida superior.

R.4. Desarrollo del momento angular sobre el eje medio-lateral del cuerpo durante la salida de atletismo con apoyo posterior (correspondiente al Capítulo 2)

En las salidas de natación la entrada en el agua fue descrita como el primer factor relevante para obtener un óptimo rendimiento (Mason et al., 2007). Una óptima posición del cuerpo en el instante del primer contacto de los nadadores con el agua y la profundidad alcanzada bajo el agua han sido mostrados factores cruciales para reducir la resistencia hidrodinámica y la deceleración que provoca el contacto del cuerpo de los nadadores con el agua (Cossor, Slawson, Shillabeer, Conway, & West, 2011; Fischer & Kibele, 2016; Tor et al., 2014; Tor, Pease, & Ball, 2015). Recientemente Fischer y Kibele (2010) encontraron una fuerte relación entre el ángulo de la cadera obtenido durante el primer contacto con el agua y el rendimiento de la salida de tal forma que un mayor ángulo de la cadera en el primer contacto con el agua minimiza la perdida de velocidad durante la entrada del cuerpo de los nadadores en el agua y permite alcanzar una optima profundidad.

La cantidad de momento angular producida durante la fase de poyete y la rotación del cuerpo de los nadadores durante la fase de vuelo es un importante factor para el rendimiento de las salidas debido a la influencia que tiene en la posición del cuerpo adoptada en el primer contacto de las manos con el agua. En este sentido un mayor momento angular en el despegue deja un mayor ángulo de entrada en el agua (Vantorre et al., 2010a).

El momento angular es una variable comúnmente utilizada en deportes como salto de trampolín, gimnasio o salto de altura, sin embargo pocos estudios incluyen esta variable en la salidas de natación (McLean et al., 2000; Vantorre et al., 2010; Vantorre et al., 2011). Consecuentemente, en esta tesis son incluidos dos estudios diferentes los cuales proveen un análisis detallado del momento angular desarrollado entre la señal de salida y la fase de deslizamiento de la salida de atletismo con apoyo posterior. A nuestro conocimiento, ambos estudios son los primeros que ofrecen un completo análisis del momento angular en las salidas de natación.

R4.1. Estrategias del momento angular en el despegue durante la salida de atletismo con apoyo posterior (correspondiente al capítulo 2, sección 1.I)

El objetivo de este estudio fue evaluar la evolución del momento angular sobre el eje medio-lateral del cuerpo en el poyete durante la salida de atletismo con apoyo posterior para identificar diferentes estrategias en el momento del despegue. Además, un análisis de los efectos del momento angular producido durante la fase de poyete sobre el rendimiento de las diferentes fases de la salida de atletismo con apoyo posterior fue realizado. Con este objetivo 36 nadadores de élite (24 hombres: 1.87 ± 0.06 m, 81.83 ± 6.99 kg, 24.71 ± 2.83 años) y 12 mujeres: (1.72 ± 0.05 m, 67.00 ± 8.42 kg, 25.67 ± 3.55 años) pertenecientes a la selección nacional alemana de natación y a la selección española de natación fueron analizados (1.82 ± 0.09 m, 76.89 ± 10.23 kg, 25.03 ± 3.07 years, 685 ± 140 puntos FINA en 100 m libres).

En la sesión de evaluación los nadadores realizaron la salida de atletismo con apoyo posterior en su posición preferida y a máxima velocidad hasta alcanzar los 15 m de distancia. La salida con un mejor tiempo a los 5 m fue analizada. El programa Kwon 3D fue utilizado para la digitalización manual de los puntos antropométricos y posterior análisis cinemático.

Después de realizar un análisis de conglomerados usando el método de Ward con la distancia Euclídea al cuadrado, cuatro perfiles diferentes de momento angular fueron identificados (figura R4.1.1): cada uno de los grupos presentó un desarrollo de momento angular diferente a lo largo de la fase de poyete y finalmente diferentes valores de momento angular en el despegue del poyete. El conglomerado 4 caracterizado por un incremento contante del momento angular a lo largo de toda la fase de poyete fue el grupo que mayores valores obtuvo en el momento del despegue. Por el contrario, el conglomerado 2 caracterizado por un descenso de los valores de momento angular en el momento del despegue de las manos fue el grupo que menores valores obtuvo en el momento del despegue. Entre los cuatro grupos es destacable el desarrollo del momento angular mostrado en el conglomerado 3. Este grupo presenta los valores más altos de momento angular hasta el momento del despegue de las manos del poyete. Sin embargo, en el momento del despegue este fue el segundo grupo con menores valores del momento angular (conglomerado 1: 103.5 ± 4.1 $s^{-1}.10^{-3}$; conglomerado 2: 81.8 ± 11.3 $s^{-1}.10^{-3}$; conglomerado 3: 91.4 ± 10.3 $s^{-1}.10^{-3}$; conglomerado 4: 132.5 ± 5.3 $s^{-1}.10^{-3}$).

Las diferencias en el desarrollo del momento angular en la fase de poyete fueron asociadas con diferencias en el ángulo de la rodilla en el momento de la señal de salida y con diferencias en el desplazamiento de los brazos desde el momento del despegue de las manos del poyete hasta el momento del despegue de los pies, lo cual fue identificado mediante el análisis del ángulo de los hombros para cada uno de los conglomerados a lo largo de la fase de poyete.

El conglomerado 4 con los mayores valores de momento angular en el momento del despegue mostró los mayores valores del ángulo de la rodilla de la pierna adelantada en la posición de preparados (conglomerado 1: 126.9 ± 12.1°; conglomerado 2: 120.9 ± 6.4°; conglomerado 3: 122.4 ± 13.5°; conglomerado 4: 138.7 ± 16.2°). En este sentido, fue asumido que un ángulo de la rodilla de la pierna adelantada en la posición de preparados de alrededor de 140° es apropiado para conseguir a mayores valores de momento angular en el despegue. De acuerdo con Slawson et al. (2012) ángulos de la rodilla de entre 135° and 145° en la posición de preparados facilitan la aplicación de mayores niveles de fuerza en el poyete y en consecuencia mayor momento angular.

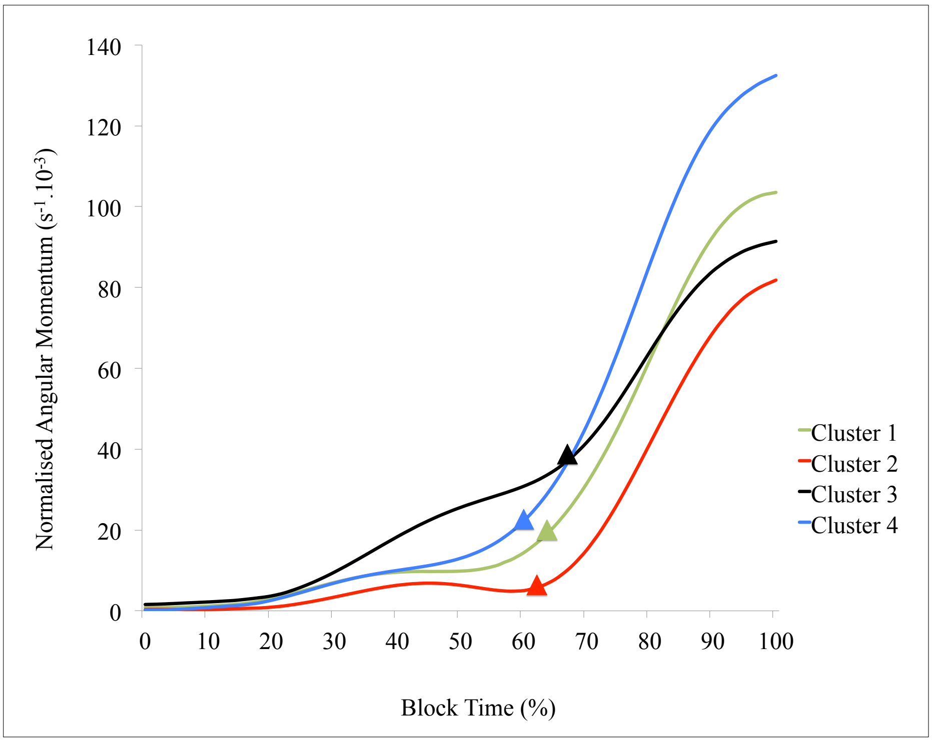

Figura R4.1.1. Estrategias para el desarrollo del momento angular sobre el poyete OSB11 y sus valores estandarizados (triángulos corresponden con el instante del despegue de las manos).

Diferencias en el desplazamiento angular de los brazos fueron asociadas con diferentes valores de momento angular durante la fase de poyete. Los resultados del ángulo de los hombros a lo largo de la fase de poyete con respecto al momento angular revelaron una asociación entre un ángulo de los hombros pequeño, con valores de entre 52° y 92° a lo largo de toda la fase de poyete y un incremento de los valores del momento angular. Por el contrario, un incremento de los valores del ángulo de los hombros y por lo tanto un movimiento hacia delante de los brazos alejándolos del tronco conducen a un descenso en los valores del momento angular en el poyete (figura R4.1.2).

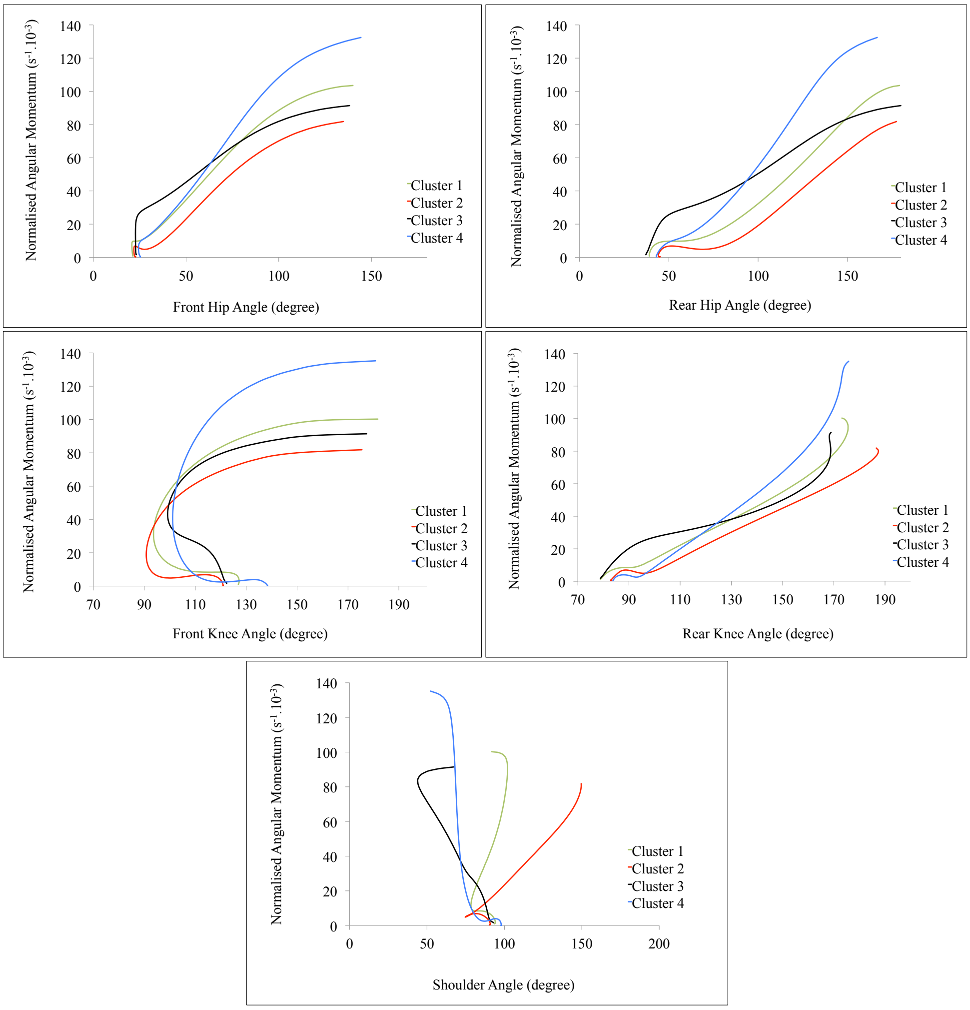

Figura R4.1.2. Relación entre el desarrollo del momento angular normalizado y el ángulo de la cadera, ángulo de la rodilla y ángulo del hombro durante la fase de poyete de la salida de atletismo con apoyo posterior.

Finalmente, valores mayores del momento angular durante la fase de poyete fueron asociados con un mejor rendimiento para la salida de atletismo con apoyo posterior en la fase de poyete y la fase de vuelo. En este sentido, el cluster 4 presentó mayores ventajas temporales en el poyete, con menores valores en el tiempo de despegue del pie atrasado, tiempo de poyete, tiempo de entrada y tiempo a 5 m respecto a los demás conglomerados con menores valores del momento angular en el despegue del poyete.

R4.2. Evaluación biomecánica del momento angular desarrollado durante la salida de atletismo con apoyo posterior (correspondiente al capítulo 2, sección 1.II)

El objetivo de este studio fue examinar cualitativamente y describir las diferencias en el desarrollo del momento angular de seis nadadores de élite (5 hombres y 1 mujer) del equipo nacional de Alemania (1.87 ± 6.6 m, 83.82 ± 9.1 kg, 24.0 ± 5.4 años, 933.2 ± 16.4 puntos FINA medidos en su prueba principal).

En la sesión de evaluación los nadadores realizaron la salida de atletismo con apoyo posterior en dos posiciones diferentes, su posición preferida y con una posición del CM más bajo, seguidas de 15 m de nado a máxima velocidad. Ambas técnicas fueron incluidas en el análisis. Para la digitalización automática y el análisis cinemático en 3D de la fase de poyete y la fase de vuelo los programas Qualisys y Visual 3D fueron utilizados. En la fase de deslizamiento se realizó un análisis 2D utilizando los programas Qualisys y Simi motion.

Un análisis de conglomerados usando el método de Ward con la distancia Euclídea al cuadrado mostró tres perfiles diferentes del momento angular desarrollado desde la señal de salida hasta la fase de deslizamiento de la salida de atletismo con apoyo posterior (Figura R.4.2.1).

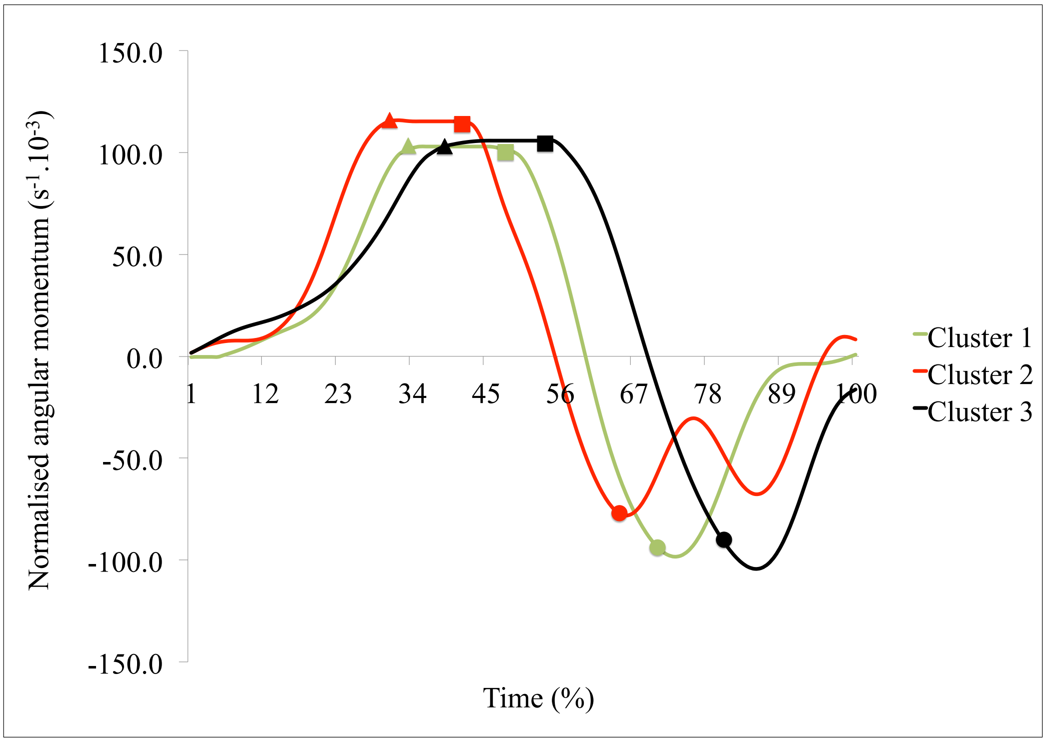

Figura R4.2.1. Estrategias para el desarrollo del momento angular normalizado producido entre el instante de la señal de salida y la fase de deslizamiento durante la salida de atletismo con apoyo posterior con valores estandarizados (triángulos corresponden al instante del despegue del poyete, cuadrados al momento del contacto de las manos con el agua y círculos al contacto de las manos con el agua).

En los tres conglomerados fue mostrado un incremento de los valores del momento angular a lo largo de toda la fase de poyete lo cual fue asociado con una posición del vector de fuerza que pasa por detrás del CM de los nadadores. Esta posición del vector fuerza indica una rotación en el sentido de las agujas del reloj y por lo tanto un desplazamiento hacia delante de los nadadores para abandonar el poyete y dirigirse hacia el agua.

Durante la fase de vuelo y de acuerdo con la ley de transferencia del momento angular, los valores se mantuvieron constantes en los tres grupos. Durante esta fase y en base a la cantidad de momento angular obtenida en el momento del despegue del poyete los nadadores pudieron mover una parte del cuerpo en una dirección mientras otros segmentos fueron movidos en dirección contraria para mantener los valores de momento angular constantes (Dapena, 2000).

Además de la cantidad de momento angular en el despegue, la rotación del cuerpo durante la fase de vuelo es dependiente del tiempo que los nadadores inviertan en esta fase. En este sentido, el conglomerado 2 con los mayores valores de momento angular en el despegue pero el menor tiempo de vuelo (conglomerado 1: 16%; conglomerado 2: 14%; conglomerado 3: 19%) parece que fue el grupo que menor rotación del cuerpo produjo a lo largo de la fase de vuelo. Consecuentemente los valores del ángulo de la cadera sugieren que los nadadores del conglomerado 2 realizaron un menor desplazamiento de las piernas durante la fase de vuelo y por lo tanto obtuvieron los menores valores del ángulo de la cadera en el primer contacto con el agua.

Una vez los nadadores alcanzaron el agua, los valores de momento angular comenzaron a descender indicando una disminución de la rotación. Este descenso de la rotación en sentido de la agujas del reloj fue asociado con la entrada en el agua de la parte superior del cuerpo donde los nadadores se mantienen en una posición vertical con el objetivo de alcanzar una profudidad optima durante la fase acuática.

Después de la entrada de la parte superior del cuerpo en el agua, los valores de momento angular comienzan a ser negativos lo que se corresponde con un ascenso de la parte superior del cuerpo y un descenso de los miembros inferiors despúes de la total inmersión de los pies en el agua con el objetivo de alcanzar una posición horizontal del cuerpo para la posterior fase de deslizamiento.

Diferentes picos de valores negativos de momento angular fueron observados entre los tres conglomerados (Conglomerado 1: -98.88 ± 9.02 $s^{-1}.10^{-3}$, conglomerado 2: -83.63 ± 6.94 $s^{-1}.10^{-3}$ y conglomerado 3: -107.22 ± 11.20 $s^{-1}.10^{-3}$) (Figura R.4.2.1). Estas diferencias fueron asociadas con diferentes amplitudes en el desplazamiento descendente de los miembros inferiores después de la total inmersión de los pies en el agua.

Es sugerido que el conglomerado 1 y 3, como consecuencia de un mayor ángulo de la cadera en el momento de la entrada en el agua, necesitaron realizar un movimiento descendente más amplio después de la inmersión de los pies con el objetivo de alcanzar una posición del cuerpo horizontal lo cual dejó mayores valores negativos de momento angular. En este sentido, mayores valores negativos de momento angular parecen ser más beneficiosos para el rendimiento de la salida de natación debido a que están asociados con una patada subacuática más larga debajo del agua lo cual supone un descenso en la pérdida de velocidad horizontal producida por la entrada de los nadadores en el agua (conglomerado 1: 0.95 ± 0.17 m/s; conglomerado 2: 1.60 ± 0.07 m/s; conglomerado 3: 0.53 ± 0.13 m/s).

Después de alcanzar los mayores valores negativos de momento angular, éstos aumentaron hasta alcanzar valores cercanos a cero lo cual se corresponde con la fase de deslizamiento de la salida de atletismo con apoyo posterior.

R.5. CONCLUSIONES GENERALES (correspondiente a general conclusions)

El principal objetivo de este estudio ha sido evaluar las características y ventajas que la salida de atletismo con apoyo posterior ofrece a los nadadores durante la fase aérea. Debido a la gran relevancia que el momento angular tiene sobre el rendimiento de las salidas de natación, se ha prestado una especial atención al momento angular y la rotación del cuerpo generados. Con este propósito, se realizaron cuatro estudios diferentes. En base a los resultados obtenidos en cada uno de los estudios realizados a lo largo de esta tesis, las principales conclusiones extraídas pueden ser resumidas en los siguientes puntos:

- Una comparación entre la salida de atletismo con apoyo posterior y la salida de agarre con el objetivo de examinar los motivos de la superioridad de la salida de atletismo con apoyo posterior. Las grandes ventajas temporales obtenidas con la salida de atletismo con apoyo posterior han sido relacionadas con la capacidad de desarrollar una gran fuerza rápidamente. EL apoyo posterior ofrece a los nadadores la posibilidad de alcanzar la aceleración máxima antes del despegue del pie atrasado del poyete. Como consecuencia los nadadores son capaces de obtener valores de velocidad horizontal en el despegue similares a las obtenidas con la salida de agarre y en un tiempo mucho mas corto. Por el contrario, con la salida de agarre los nadadores necesitan invertir un mayor tiempo en el poyete para conseguir los mismos valores de velocidad horizontal en el momento del despegue.

- El desplazamiento que la pierna atrasada realiza durante la fase de poyete supone una importante ventaja para el rendimiento de la salida de atletismo con apoyo posterior. Este desplazamiento da lugar una posición del cuerpo más vertical hacia abajo en el momento del despegue del poyete y una mayor altura de las piernas con respecto al tronco (mayor ángulo final del cuerpo) en el momento del contacto con el agua. Esta posición al contacto con el agua reduce la pérdida de velocidad como consecuencia de la entrada de los nadadores en el agua.

- La relación entre las variables implicadas en la fase de poyete y la fase de vuelo fue examinada con el objetivo de determinar los factores claves para mejorar la salida de atletismo con apoyo posterior.

≈ Un mayor y más rápido desarrollo de la aceleración horizontal producida durante la fase de poyete es la clave del mejor rendimiento de la salida de atletismo con apoyo posterior. Este perfil del desarrollo de la aceleración horizontal permite obtener un menor tiempo de poyete, una mayor velocidad horizontal el el momento del despegue del poyete, una fase de vuelo más larga, un mayor ángulo final del cuerpo, una menor pérdida de velocidad durante la entrada en el agua y finalmente un tiempo a los 5 m más corto.

≈ Un menor desplazamiento de la pierna atrasada durante la fase de poyete es necesaria para producir una fase de vuelo más larga. La fase de vuelo más larga va a permitir incrementar la rotación del cuerpo en el aire y alcanzar una mayor altura de las piernas con respecto al tronco en el momento del contacto con el agua. Como consecuencia es reducida la pérdida de velocidad producida durante la entrada de los nadadores en el agua y se obtienen tiempos a 5 m más cortos.

- La cantidad de rotación producida durante el vuelo depende de la cantidad de momento angular que los nadadores obtengan en el momento del despegue del poyete. En la salida de atletismo con apoyo posterior, la rotación del cuerpo en el aire es principalmente producida por un desplazamiento ascendente de la pierna adelantada aproximándola hacia la pierna atrasada con el objetivo de entrar en el agua con ambas piernas juntas. Por el contrario, los principales movimientos rotacionales durante la fase de vuelo de la salida de agarre son producidos con el tronco realizado un movimiento en la dirección de las agujas del reloj de forma que se dirigen hacia las piernas. A pesar de las diferencias rotacionales, ambas salidas mantienen las mismas diferencias obtenidas en el poyete hasta alcanzar la distancia de 5 m.

- Un análisis del momento angular desarrollado en el poyete fue realizado durante la salida de atletismo con apoyo posterior con el objetivo de identificar los diferentes perfiles de momento angular producidos en el momento del despegue del poyete, las variables implicadas en el desarrollo del momento angular y con el objetivo de evaluar el efecto del momento angular en el rendimiento de la salida de atletismo con apoyo posterior. Cuatro perfiles diferentes de momento angular fueron identificados. El perfil con el mayor momento angular fue asociado con un tiempo a 5 m más corto.

- Un mayor momento angular en el momento del despegue fue relacionado con un mayor ángulo de la rodilla en la position de preparados. Estos resultados fueron asociados al mayor desarrollo de fuerza que produce un mayor ángulo de la rodilla en este momento.

- Un desplazamiento hacia atrás de los brazos de forma que éstos se aproximen al tronco manteniendo un ángulo de los hombros de entre 52° y 92° durante toda la fase de poyete fue asociada con un incremento de la cantidad de momento angular producido durante la fase de poyete. Por el contrario, la cantidad de momento angular se reduce cuando los brazos se mueven hacia delante alejándose del cuerpo.

- El estudio cualitativo del momento angular desarrollado durante la salida de atletismo con apoyo posterior ha permitido conocer que una óptima estrategia entre un incremento de la cantidad de momento angular en la fase de poyete y un largo tiempo de vuelo es necesario para incrementar la rotación del cuerpo durante la fase de vuelo. Una mayor rotación del cuerpo producido como consecuencia de un mayor movimiento ascendente de los miembros inferiores da lugar a un ángulo de la cadera mayor en el instante del primer contacto con el agua. Esta posición del cuerpo fue sugerida óptima para incrementar la rotación en dirección contraria a la agujas del reloj producida después de la entrada de los pies en el agua. Una mayor rotación en dirección contraria a las agujas del reloj fue asociada con una patada subacuática y una reducción en la pérdida de la velocidad horizontal generada bajo el agua.

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LIST OF PUBLICATIONS

- Taladriz, S., de la Fuente, B., & Arellano, R. (2016). *Analysis of angular momentum effect on swimming kick-start performance*. Journal of Biomechanics. http://dx.doi.org/10.1016/j.jbiomech.2016.04.012. (I.F. 2.75)

- Taladriz, S., Fischer, S., de la Fuente, B., & Arellano, R., Kibele, A. *Take-off strategies in swim starts from the OSB11 block with reference to angular momentum*. Submitted

- Taladriz, S., de la Fuente, B., & Arellano, R. *Advantages on the airborne phase performance of swim start from the OSB11 starting block*. Submmited

- Taladriz, S., de la Fuente, B., & Arellano, R. *Ventral swimming starts, changes and recent evolution: A review*. Submmited

Other relevant publications related with this thesis:

- Taladriz, S., de la Fuente, B., Arellano, R. The kick start: key of its superiority. In: F. Colloud (Ed.) *33rd International Conference on Biomechanics in Sports*. Poitiers, France.

ACKNOWLEDGES

Gracias a mi director de tesis, Raúl Arellano, gracias por abrirme las puertas de tu laboratorio y ofrecerme todos los medios que han estado en tu mano para para llevar a cabo esta tesis.

Gracias a Blanca de la Fuente, por aceptar este reto sabiendo que no iba a ser nada fácil. Gracias por tu apoyo, por tus consejos y por escucharme y respaldarme en los peores momentos. Gracias por invertir tu tiempo en sacar esta tesis adelante.

Gracias a Jesús Dapena, gracias por enseñarme todo lo que sé del momento angular. Gracias por validar todos y cada uno de los resultados que conforman el primer capítulo de esta tesis de forma desinteresada. Gracias por tu paciencia y por cada uno de los vídeos e informes que me han ayudado a entender cosas incomprensibles para mi en un inicio.

Thanks to Karla de Jesus, Elaine Tor, Jodi Cossor and Christopher Connaboy for increasing the quality of this thesis with their constructive comments after reading the thesis.

Gracias a Esther Morales, a Rocío Domínguez y a Gracia López, gracias por vuestra ayuda y por hacerme sentir que siempre podía contar con vosotras.

Gracias a Paco Cuenca y a Sara Manzano, gracias por tantas mañanas de risas en el laboratorio.

Gracias a Cristina Cadenas y Clara Sánchez, gracias por ofrecerme vuestra amistad, por vuestro apoyo y ayuda. Gracias por tantos cotilleos y tantas risas juntas. Gracias por hacerme mis años granadinos más fáciles y felices.

Thanks to Armin Kibele, for accepting me in your group reseach. Thanks for opening the door of your house and making me feel at home. Thanks for teaching me what is the investigation and how do it. Thanks for your patience and your generosity. Thanks for giving value to my work and sharing your knowledges with me. Thanks for increasing the quality of this thesis.

Thanks to Sebastian Fischer for guiding me in each of research projects. Thanks for your patience, kindness and generosity. Thanks for your great effort and help in each work made in Kassel. Thanks for teaching me new things and sharing with me your knowledges.

Thanks to Nils Eckardt for all hours that you invested in my thesis unselfishly. Thanks for your help and generosity and for helping me to carried out my project even forgetting your own projects. Thanks for all moments of laugh and all moments of angry.

Thanks to Claudia Classen for helping me during my time in Kassel and make me feel that I could count on you.

To the research group CIFI2D (University of Porto). Thanks to Joao Paulo Vilas-Boas and Ricardo Fernandes for sharing with me their work and tools. Thanks to Karla de Jesus and Kelly de Jesus for teaching me new methods of working and sharing their knowledges with me.

Gracias a Max, un alemán muy español, gracias por hacerme fácil mi llegada a Alemania y por invertir tantas horas para que estuviese bien tan lejos de casa.

Gracias a Ainhoa Terán, una española muy alemana, gracias por abrirme las puertas de tu casa, ofrecerme tu amistad y hacerme sentir como si te conociese de toda la vida. Gracias por tu compañía, tu generosidad y tu ayuda desinteresada, por escucharme y soportarme.

Gracias a mis amigas, Miriam, Leti y Vero, gracias por no olvidaros de mi. Por ofrecerme siempre vuestra ayuda y contar siempre con vuestro apoyo. Gracias por vuestra paciencia y generosidad ante tantos momentos de ausencia.

Gracias a mis padres por el gran esfuerzo que habéis hecho para que pudiese hacer esta tesis. Gracias por ofrecerme la oportunidad de tener un futuro mejor. Gracias a mi tía, Flora, gracias por ser una lección de vida constante, por enseñarme a ser feliz y a sonreír sea cual sea la situación.

Gracias a mi hermana, Patricia Taladriz, gracias por ser como eres. Gracias por ser mi guía, mi ejemplo a seguir y el espejo en el que mirarme cada día. Gracias por enseñarme y abrirme nuevos caminos. Gracias por tu apoyo, tus consejos y tu ayuda. Gracias por todas las horas y días que has invertido en esta tesis. Gracias por tu compañía aún estando a miles de quilómetros, gracias por escucharme y gracias por reír y llorar conmigo.

Gracias a ti Raúl B., la persona especial que me acompaña cada día, gracias por soportar todos estos años frente a un ordenador, gracias por aguantar mi mal humor a causa de problemas ajenos a ti. Gracias por aguantar mis ausencias incluso estando bajo el mismo techo. Gracias por hacer fáciles las decisiones difíciles y por apoyarme siempre aunque eso suponga estar lejos de las personas que más quieres. Gracias por reírte conmigo en los momentos felices y por hacerme reír en los más tristes. Gracias por recorrer este camino conmigo y gracias por tu enorme paciencia y generosidad.

Gracias a todos los que de una manera u otra habéis formado parte de estos años de tesis.