UNIVERSITY OF PORTO
Faculty of Sport
Centre of Research, Education,
Innovation and Intervention in Sport

# Studies of performance in swimming

## Biomechanical analysis of relay starting techniques: new technologic and conceptual instruments

Academic dissertation submitted with the purpose of obtaining a doctoral degree in Sport Sciences according to the Decree-Law 74/2006 from March 24th.

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**Key Words:** *Biomechanics, Starting Block, Relay Changeover, Track Start, Active Starting Force*

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# List of Publications

This doctoral thesis is based on the following scientific papers, which are referred in the text by their Arabic numerals, respectively:

1. Mourão, L., de Jesus, K., Roesler, H., Machado, L., Fernandes, R., Vilas-Boas, J., Vaz, M. (2015). Effective swimmer's action during the grab start technique. Submitted to ***PLOS ONE***.
2. Mourão, L., Machado, L., Fernandes, R., Vilas-Boas, J., Vaz, M. (2011). Force and Centre of Pressure evaluation with an instrumented platform for swimming performance optimization. **Portuguese Journal of Sport Sciences** Vol.11 (Suppl. 2), pp 915-917.
3. Mourão, L., Vilas-Boas, J., Viriato, N., Monteiro, J., Vaz, M. A. (2012). Didactic Force Plate for animal gait performance assessment. **ICEM 15 Proceedings, 15th International Conference on Experimental Mechanics**, Fac. of Engineering University of Porto & Portuguese Society for Experimental Mechanics, Porto, pp 361-362.
4. Mourão, L., de Jesus, K., Viriato, N., Vilas-Boas, J., Monteiro, J., Vaz, M. (2015) A.Design and construction of a 3D force plate prototype for developing an instrumented swimming start block. Submitted to ***Journal of Biomedical Engineering and Informatics.***

Also a **Patent** was extracted from this work:

----------NPAT 212/14 and INPI nº 108229

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Equation (19) $$\begin{cases} R_{h\_Active}(t) = GRF_h(t) - R_{h\_Passive}(t) \\ R_{v\_Active}(t) = GRF_v(t) - R_{v\_Passive}(t) \end{cases}$$ **81**

Equation (20) $$\begin{cases} L_1 \rightarrow L_2 = \sqrt[3]{\frac{m_2}{m_1}} L_1 \\ V_1 \rightarrow V_2 = \frac{m_2}{m_1} V_1 \\ I_1 \rightarrow I_2 = \left(\sqrt[3]{\frac{m_2}{m_1}}\right)^2 \frac{m_2}{m_1} I_1 \end{cases}$$ **91**

# Abstract

Swimming starts are very important, especially in short events. Previous studies are mostly based in kinematic assessment of starting phases, as block phase, flight phase, entry phase, glide phase, leg kicking phase and swimming phase. However, the block phase is determinant of the remaining phases and spatial and time resolution, at that particular phase, is where uncertainty in kinematic measurements is higher. At that earlier stage of the start, force measurements can give a strong contribute to aid the assessment of the block phase start performance. Also, inertial effects should be assessed, once they disturb the motion responsiveness to voluntary action forces, a central issue to aid coaching. Compared to kinematic based, few studies address the kinetics of swimming starts, and none discriminated to date the inertial and muscular contributions to force generation.

Therefore it is important to develop a device that completely assesses force generation produced by the swimmer while in block contact, as well as to develop a solution for distinguish passive (inertial) from active (muscular) force generation. Those were the central aims of this thesis.

The thesis is composed of six chapters: chapter 1 is the Introduction. Chapter 2 is a survey of the work done in dynamometry and its contribution for swimming start performance analysis. Chapter 3 is divided in two parts: the part A involves the preliminary tests for a force load cell implementation, the dynamometric device core component; part B concerns to the replication of the decided core, the ecology of the spatial allocation in order to instrument a mimethized regulamentar starting block (which is the external physical configuration of the dynamometric device) and its technical manual (under temporary patent NPAT 212/14 publication reserve). Chapter 4 is an original development of an algorithm for the assessment and splitting of the swimmers' propulsive and inertial forces (passive forces due to dead weight). Chapter 5 presents some dynamometric device applications, where Chapter 5.1 addresses force assessment in relay changeovers, while Chapter 5.2 applies the passive-active splitting algorithm to track-start. Chapter 6 is the synopsis of findings and conclusions sections. With this thesis it was possible to develop an innovative dynamometric measurement solution for swimming starts and changeovers, an algorithm for discrimination of inertial active force production during starts, and the first description of the kinetics of changeover starts; three new advances that increases knowledge on swimming starts biomechanics and availability of cutting edge technology.

**Keywords:** kinetics, dynamometry 3D 6DoF, biomechanics, active-passive force, swimming relay changeovers/starts.

# Resumo

As partidas em natação são muito importantes, especialmente em provas de curta duração. Os estudos em natação são baseados principalmente na cinemática avaliando fases da partida como fase do bloco, fase de voo, a fase de entrada, fase deslizante, fase de pernada e fase de braçada (Vantorre 2010). No entanto, a fase de bloco, sendo a mais consequente para as outras fases, e, dada a resolução espacial e temporal da cinemática, é também onde a incerteza nas medições posicionais é maior. Nessa fase inicial, a fase do bloco, as medidas de força podem dar um forte contributo para auxiliar a avaliação do desempenho da partida. Além disso, os efeitos da inércia, alterando a resposta em movimento mecânico resultante de acção de forças voluntárias, devem ser avaliadas, a fim de auxiliar o treino. Comparativamente aos estudos cinemáticos, poucos estudos acedem à cinética das partidas em natação, e nenhum discriminou, até à data, as contribuições inerciais e musculares da força gerada.

Por isso, é importante a criação de um dispositivo que avalie a geração de força produzida pelo nadador, enquanto no bloco. É objectivo complementar deste trabalho a separação dessa força em componentes de força passiva e de força activa.

Este documento de Tese é constituído por sete capítulos: o Capítulo 1 é a introdução. O Capítulo 2I é um levantamento do trabalho realizado e contribuição da dinamometria para análise de desempenho em partidas de natação. O Capítulo 3 é dividido em duas partes: a parte A descreve o *design* preliminar de uma célula de carga, componente principal na central dinamométrica; a parte B consta da replicação do componente principal optado, a disposição das réplicas de acordo com *layout* conveniente e o manual técnico (sob reserva de publicação por patente temporária NPAT 212/14) do bloco de partida instrumentado (central dinamométrica). O Capítulo 4 é um desenvolvimento original de um algoritmo para a avaliação e separação de forças propulsoras (forças activas) e estruturais dos nadadores (forças passivas, devido ao peso morto). O Capitulo 5 apresenta aplicações da central dinamométrica, sendo o Sub-Capitulo 5.1 dedicado a medidas de força gerada e avaliada com central dinamométrica em rendições e o Sub-Capitulo 5.2 uma aplicação do conceito de separação de força activa-passiva à *track-start* em condições da sua aplicabilidade. O Capítulo 6 é uma sinopse e conclusão. Com esta tese foi possível desenvolver uma solução de medida dinamométrica inovadora para partidas e rendições em natação, um algoritmo para discriminação da força activa produzida durante as partidas, e a primeira descrição de cinética envolvida em rendições de estafetas; três novos avanços que incrementam o conhecimento na biomecânica de partidas em natação e disponibilidade de tecnologia de ponta.

**Palavras-chave:** cinética, dinamometria 3D 6DoF, biomecânica, forças activa-passiva, partidas estafetas em natação.

# List of Abbreviations

| | |
|---|---|
| 3D-6DoF | 3 dimension force, 6 degrees of freedom (includes moment of force) |
| $\vec{a}$ | Acceleration vector $\left(m \cdot s^{-2}\right)$ |
| ADC | Analog to Digital Converter |
| CM | Centre of Mass |
| $COP$ | Centre of Pressure point |
| $\overrightarrow{COP}$ | $COP$ planar or 3D position $(m)$ |
| $\varepsilon_i$ | strain $(\mu m / m)$ |
| $\vec{F}$ , $\left(F_x, F_y, F_z\right)$ , $\vec{w}$ | Force vector, Force components, Weight $(N)$ |
| FET, n-MOSFET | Field Effect Transistor, n-channel Metal-Oxide Semiconductor FET |
| FINA | Fedération Internationale de Natation |
| GRF, $\overrightarrow{GRF}$ | Ground Reaction Force magnitude, vector $(N)$ |
| $I$ | Inertia tensor $\left(kg \cdot m^2\right)$ |
| ISB | International Society of Biomechanics |
| $\vec{M}$ , $\left(M_x, M_y, M_z\right)$ | Moment of Force vector, components $(N \cdot m)$ |
| $\Delta\vec{p}$ | Impulse $\left(kg \cdot m \cdot s^{-1}, N \cdot s\right)$ |
| PC | Personal Computer |
| SI units | International System of Units |
| USB | Universal Serial Bus, pc communication protocol |

| | |
|---|---|
| $\vec{v}$ | Velocity $\left(m \cdot s^{-1}\right)$ |
| $\left(x_{CoP}, y_{CoP}\right)$ | $COP$ plane position $\left(m\right)$ |
| $\left(x_{CoP}, y_{CoP}, h\right)$ | $COP$ 3D position $\left(m\right)$ |

# Chapter 1.

## Introduction

Swimming starts can be categorized in families depending on the premises shown in Figure 1 (Vilas-Boas *et al.*, 2003). Premises include stimulus nature and postural swimmer body inter-segmental patterns and dynamics guiding to, at least in the ventral events, the conventional names of the standard start techniques/variants.

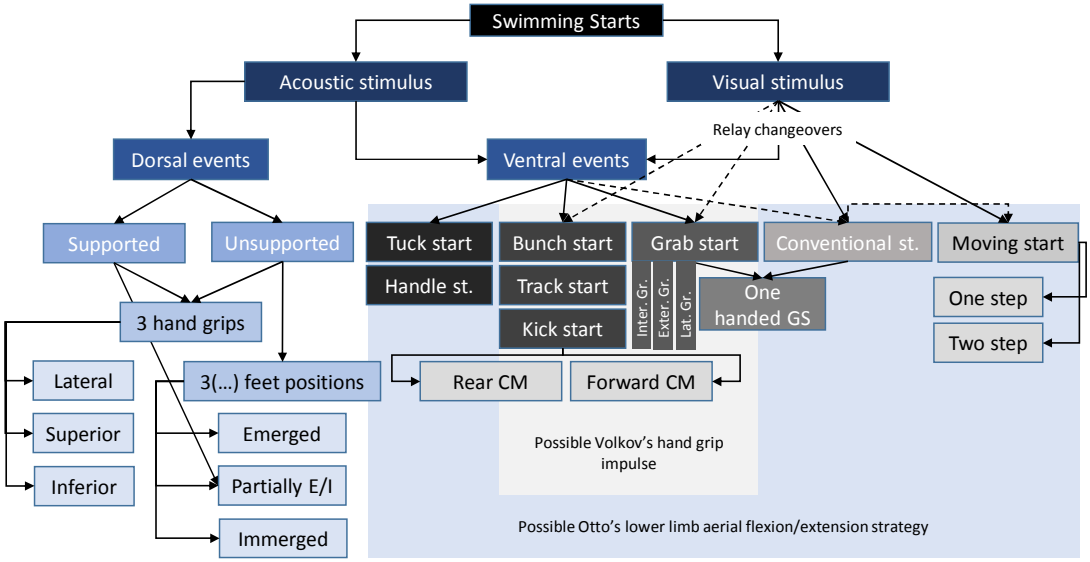


***Figure 1*** *Categorization of body intersegment allocation (not named) dorsal events and (named) ventral events. Synthesis of the currently practiced and previously described swimming starts. Adapted from Vilas-Boas and Fernandes (2003). CM = Centre of Mass, E = Emerged, I = Immerged.*

Dorsal starts, more scarcely studied, are currently object of concomitant studied in another PhD project. The ventral individual events, meanwhile, have been much more studied by the scientific community, and their features and relations are extensively detailed in Figure 1. Despite the kick, or track start, and still also the grab start keep as the more studied techniques, the conventional or traditional start, the handle start and the moving starts should remain serious topics of interest. This is so despite the track and the grab start covers almost 100% of the ventral competitive performed starts in the most relevant world level events.

Indeed, the conventional start and the moving starts remain also much practiced during the changeover starts actions in relay events, while the handle start suggests a new technical possibility in case of availability of the proper features at the starting block. In synthesis:

i) Conventional Start (CS)

This start is characterized by swing upper limbs and is, perhaps, the oldest swimming start technique (Zatsiorsky, Bulgakova, & Chaplinsky, 1979). It has been considered two and three variants corresponding to the arm swing different possibilities. Nowadays, the conventional start is often used during changeover starts during relay events, once the time in block may be not relevant (swimmer may start moving before the colleague arrives) and the starting impulse may be quite high – inclusively higher than other techniques, such as the grab start (T. Takeda, Takagi, & Tsubakimoto, 2010).

ii) grab start (GS)

The GS is a swimming start technique first characterized by front of block simultaneous limb contact area alignment. The three variants can be, therefore, presented depending on the relative position of the hands to feet, i.e., hands between feet (Inter. Gr., interfeet GS), feet between hands (Exter. Gr., extern to feet GS) and lateral hand position (Lat. Gr., laterally to front of the block hand positioned GS). Higher GS stability (Maglischo, 2003) has been pointed as criteria for its recommendation while a mixing between conventional start (not used anymore except for changeovers) and grab start allows the once proposed (Galbraith, Scurr, Hencken, Wood, & Graham-Smith, 2008) but never relevantly performed “one handed GS”.

iii) tuck start (TuS) and handle start (HS)

The TuS is earlier to HS and is characterized by hands positioned laterally to the block cover cap and by grouped body segments with CM projection forward, reaching, inclusively, a position ahead of the upper surface of the starting block. The HS is a successor variant, mainly characterized by hands positioned laterally to the block, using small grips positioned parallel to lateral border of start block, and by the forward positioned Centre of Mass or CM. In Australia, and named HS variant as well, it is traditional the hands grasp the ring-like front-top of the handgrips allowing the CM in clear forward position relative to the front of the block.

iv) track start (TrS), Bunch Start (BS) and kick start (KS),

Bunch start is the earlier asymmetric lower limb positioned start technique. The track start is characterized by front lower limb (left or right depending on subject laterality dominance), with the introduction of the FINA's facilities rules backplate it has been renamed kick start (named by similarity to terrestrial race start inheritance). Variants can be also distinguished by CM anterior-posterior relative to front of block position splitting the rear and forward CM cases;

In addition, visual stimulus should be added to ventral events, in substitution of the acoustic stimulus, allowing the inclusion of relay changeovers, where any of these earlier ventral techniques can be included. There is no real token to be shared in swimming changeovers being substituted by simultaneous contact to block by both swimmers. Such simultaneity, however, is still legal if falls to minimum of -0.03s (negative value stands for earlier force record take off, or zero force, to arrival in the relay changeover) since Omega tests done in 1982 to 1984, while inspecting time differences between force vanish and toe contact loss. Also, as visual stimulae are provided by the approaching swimmer, postural differences, as cervical upward orientation, are produced. The fast "handshake" match of both swimmers promotes the interest of the so called "in movement" starts. These starts forecast initial moment and certainly, while providing initial higher velocity compared to resting start techniques, would lead to enhancement in changeover total time minimization, speed maximization and, hopefully, maximum flight range. The conventional, or no-step technique, is applied with an inverted pendular back and forth movement (with the feet in front of block positioned) is maintained until the arriving swimmer gets contact to block. In the one step technique, one limb is rear positioned and the propulsion is provided by the two feet after a step of alignment of both feet. In the two step both feet are aligned in a rear position (not frontal) implying two frontal alignment steps followed by simultaneous propulsion and takeoff.

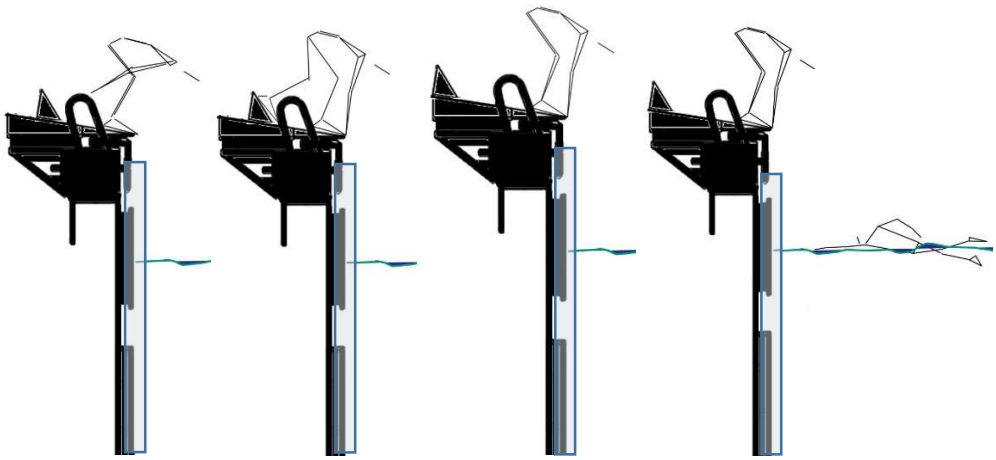

***Figure 2*** *Schematics of the limb positioning in HS, KS, GS and GS in relay changeover.*

Previous published studies are mostly based in kinematic assessment of starting phases, as block phase, flight phase, entry phase, glide phase, leg kicking phase and swimming phase (Vantorre, Seifert, Fernandes, Vilas-Boas, & Chollet, 2010a). However, block phase is most consequential to the other phases and where spatial and time resolution scores higher uncertainty in kinematic measurements. At that earlier stage of the start, force measurements can give a strong contribute to aid the assessment of the block phase start performance. These forces are called ground reaction forces $(GRF)$. Also, inertial effects, coupling to mechanical responsiveness to voluntary action forces, should be assessed, in order to aid coaching.

Therefore it is important to provide a device that assesses force generation produced by the swimmer while in block contact, as well as a solution to split passive from active force generation during the task. These are the main purposes of this thesis.

This thesis is a set of seven chapters defining the pathway to achieve the aforesaid goals.

In the first chapter, this introduction itself, it is intended to present the problem, objectives and thesis structure.

The second chapter provides a survey of the main literature that discloses the most part of the work done on swimming science using kinetics or GRF measurements during the starts. It is tried out to list solely the works done and their main characteristics, while it is left for the discussion chapter the analysis of

the main pros and cons of each work and how the contributions of this thesis can provide solution to solve most part of the limitations of previous works.

The third chapter establishes the foundations of the dynamometry to be applied and all the technical pathways for the achievement and the implementation of a dedicated dynamometric device for ventral starts analysis in swimming. There are several sub-steps that got to be considered. First, in Chapter 3.1, it is presented the didactical device that was previously developed in order to introduce and disambiguate the requirements of a complete 3D 6DOF platform. This achievement is completed on the Chapter 3.2 (under patent reserve of publication) that completes and details the presentation of the dynamometric device. It includes the development and the novel introduction of adaptations required to the relatively high dimension of data acquisition to be provided, as well as modules to provide synchronism to, eventually, different chassis with different communication technologies. Data acquired can be, almost immediately, presented to the swimmer, allowing a good bio-feedback transient responsiveness, adequate for coaching advice.

The fourth chapter introduces a novel approach for the study of the inertial effects of the swimmer's body during the transient body positions assumed during an example start, allowing the Active from Passive split of exerted forces. Such analytic tool was mostly anchored on the particular case of grab start, based on its simplest geometrical description. However, for the other start techniques at the final contact with the block, it is always true that a sole limb or both lower limbs are in contact with the anterior limit of the block, producing a GRF pattern compatible to the new-born description. In this case, this technique can be applied to the other ventral swimming start techniques.

The third and fourth chapter are considered the main original contribution of this work.

The fifth chapter is dedicated to relay changeovers specific application of the dynamometric device and the mathematical tool for splitting active from passive force. It is divided in two subchapters: subchapter 5.1 exhibits the extended possibilities of this dynamometric device to measure force-time curves during relay changeovers, if aided by underwater platforms. Four changeover techniques (or variants) have been studied: traditional or conventional, one step, two step and track start. These two last techniques, though, are different from the

regular ventral techniques as the swimmer has his/her head necessarily more upward positioned (cervical extension) in order to allow observation of the swimmer finishing his lap. The Chapter 5.2 applies the splitting technique to the individual track start in the sub phase aforesaid to assess the Passive and Active forces exerted by the swimmer where biomechanical premises are present.

Chapter 6 is the Synopsis of findings and conclusions sections.

The Figure 3 depicts the flow diagram structure of this thesis.

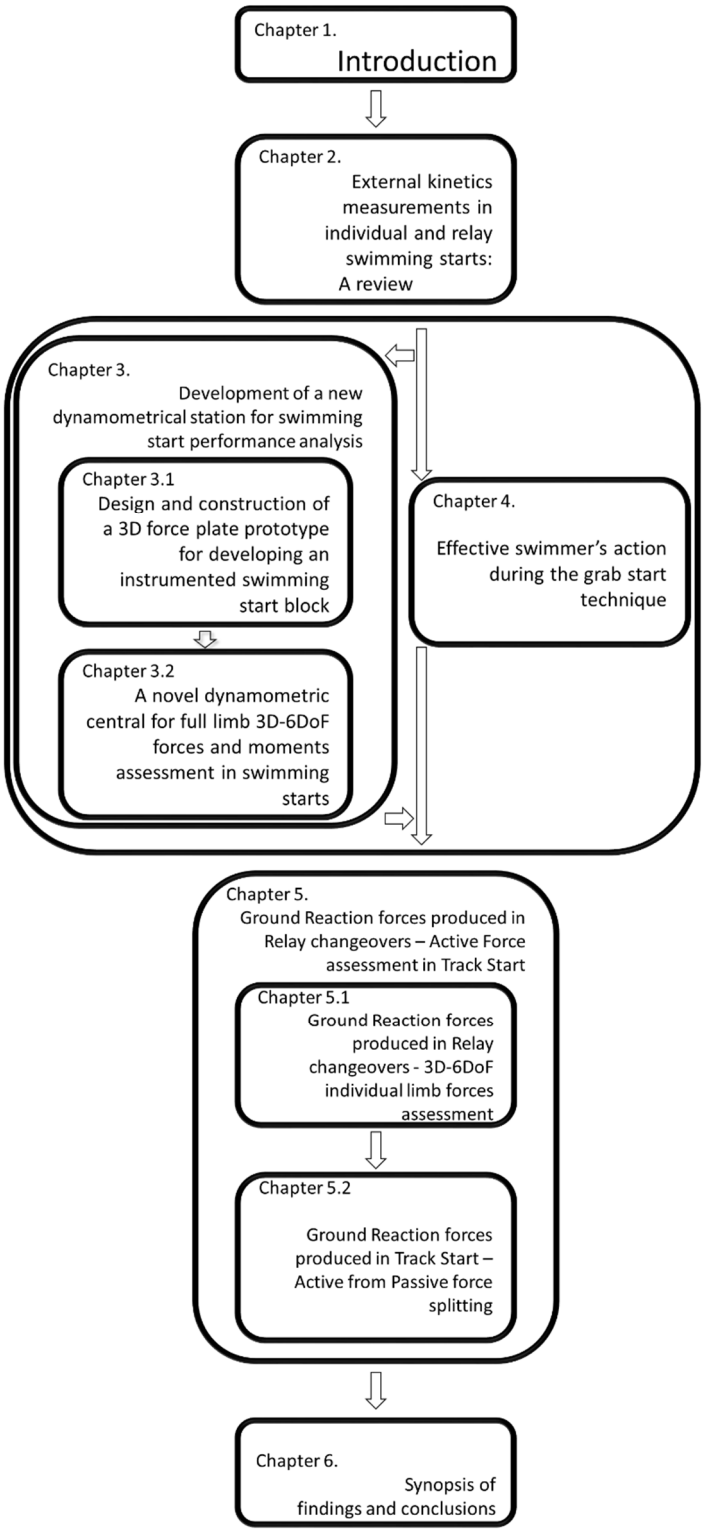


***Figure 3*** *- Schematics of the thesis structure.*

## References


Galbraith, H., Scurr, J., Hencken, C., Wood, L., & Graham-Smith, P. (2008). Biomechanical comparison of the track start and the modified one-handed track start in competitive swimming: An intervention study. *Journal of applied biomechanics, 24*(4), 307-315.

Maglischo, E. W. (2003). *Swimming fastest* (Champaign Ill ed.): Human Kinetics.

Takeda, T., Takagi, H., & Tsubakimoto, S. (2010). *Comparison among three types of relay starts in competitive.* Paper presented at the Biomechanics and Medicine in Swimming XI.

Vantorre, J., Seifert, L., Fernandes, R., Vilas-Boas, J., & Chollet, D. (2010a). Kinematical profiling of the front crawl start. *International journal of sports medicine, 31*(01), 16-21.

Vilas-Boas, J. P., Cruz, J., Sousa, F., Conceicao, F., Fernandes, R., & Carvalho, J. (2003). *Biomechanical analysis of ventral swimming starts: Comparison of the grab start with two track-start techniques.* Paper presented at the Biomechanics and Medicine in Swimming IX, Saint-Étienne, France.

Zatsiorsky, V., Bulgakova, N. Z., & Chaplinsky, N. (1979). *Biomechanical analysis of starting techniques in swimming*.

# Chapter 2.

## External kinetics measurements in individual and relay swimming starts: A review

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### Abstract

This study aimed to present a literature review on the external kinetics of swimming starts for the purposes of summarizing and highlighting existing knowledge, identifying gaps and limitations and challenging new researchers for future projects. A preliminary literature search was performed using relevant electronic databases, only for English written documents published before September 2013. Keywords including “swimming” and “start” were used to locate documents. Proceedings of the scientific conferences of Biomechanics and

Medicine in Swimming (BMS) and the International Society of Biomechanics in Sports (ISBS) from 1970 and 1983, respectively, to 2013 were examined. Included studies were experimental biomechanical approaches in laboratory setting relating to external kinetics assessments on swimming starts. Twenty-eight studies were included in this review, of which 10 are peer-review journal articles and 18 are proceedings from the BMS and ISBS Congress series. From the overall included studies, 82.14% analyzed the individual ventral starts, followed by 14.28% devoted to backstroke start, and only 3.57% analyzing relay starts. Twenty-five per cent from the overall ventral starting studies measured the external horizontal and vertical forces reacting on the swimmer's hands and only one research group has yet published about the upper limbs horizontal force on the backstroke start. Previous studies have presented unique contribution in swimming start kinetics; however, future researches should focus on devices capabilities improvements based on the current starting block configuration, mainly for dorsal and relay starting kinetics analysis purposes, and considering 3D-6DOF analysis of the forces exerted by each of the four limbs.

Keywords: *biomechanics, forces, moments, swimming analysis, starting techniques*

## Introduction

The swimming start, defined by the time period between the starting signal until the swimmer's head achieve 15 m (Vantorre, Seifert, Fernandes, Vilas Boas, & Chollet, 2010b), is an important part of short and middle distance swimming events. For example, 15 m after the start, the second-placed at men's 100 m freestyle at Barcelona 2013 Swimming World Championships was 0.08 s slower than the winner, and the final race time difference was only 0.11 s. The importance of the start is emphasized further in middle distance events, since, in the same swimming competition, the winner at men's 200 m freestyle performed the fastest 15 m starting time during the final. In fact, at the recent elite level swimming competitions it is not the swimming speed that wins races but rather the better technicians in starts and also turns (Mason, Mackintosh, & Pease, 2012).

The swimming start is composed of several phases: block/wall, flight, entry, glide, leg kicking and swimming (S. Slawson, Conway, P., Cossor, J., Chakravorti, N., West, A. , 2013; Vantorre et al., 2010a), which are interdependent (Vantorre et al., 2010a). According to Hay, Guimaraes, and Grimston (1983) and Mason, Alcock, and Fowlie (2007), the block phase determines what happens in flight and subsequently during the underwater phase, respectively. (Vantorre et al., 2010a) have verified that the block phase negatively correlates with the starting time and advised swimmers to perform a rapid reaction to the starting signal and impulse over the starting block. In fact, the study of the ground reaction forces, which generate the swimmers' movements that attend such above-mentioned requirements have been conducted since the 1970's. To date, Elliott (1971) were the pioneer on the starting block instrumentation for direct force measurements.

Despite the well-accepted relevance of the external kinetics assessment and understanding at swimming starts, no former review was found in the literature about the different dynamometric devices and respective parameters assessed. It would be interesting to find scientific evidence and report the advancements pertaining to the direct forces measurement in individual and relay swimming starts. Considering that the international swimming rules for individual and relay starting recommendations have changed, and the starting block has undergone many adaptations, it is crucial to gather the most relevant studies in a synthesised critical review. This study reviewed the swimming literature on starting external kinetics for the purposes of summarizing and highlighting existing knowledge, identifying gaps and limitations and challenging new researchers for future projects.

## Methods

A preliminary literature search was performed using PubMed, SportDiscus, Scopus and ISI Web of Knowledge electronic databases, only for English written documents published before September 2013. Keywords including "swimming" and "start" were used to locate documents. Proceedings of the scientific conferences of Biomechanics and Medicine in Swimming (BMS) and the International Society of Biomechanics in Sports (ISBS) from 1970 and 1983,

respectively, to 2013 were examined. Included studies were experimental biomechanical approaches in laboratory setting relating to external kinetic assessments on swimming starts. The documents that were available only as abstracts and duplicated studies were excluded.

## Results

Table 1 display the ultimately 28 studies included in this review, 10 of which are peer-review journal articles and 18 are proceedings from the BMS and ISBS Congress series. Twenty-five and 46.42% from the overall starting studies applied the strain gauges and piezoelectric crystals technology, respectively.

*Table 1. The 28 studies that assessed the external forces in individual ventral and dorsal and relay starts, and the corresponding general description.*

| Authors | Start technique | Forces assessed |
|---|---|---|
| Elliott (1971) | Ventral | Horizontal lower limbs |
| Cavanagh, Palmgren, and Kerr (1975) | Grab | Horizontal and vertical upper limbs |
| Stevenson and Morehouse (1978) | Grab | Horizontal and vertical upper limbs |
| Shierman (1978) | Grab | Horizontal and vertical lower limbs |
| Zatsiorsky et al. (1979) | Arm swing, grab and track | Horizontal and vertical lower limbs |
| Hay et al. (1983) | Grab | Horizontal upper and lower limbs |
| Vilas-Boas *et al.* (2000) | Track | Horizontal, vertical and resultant |
| Naemi *et al.* (2000) | Grab | Horizontal and vertical lower limbs |
| Kruger *et al.* (2003) | Grab and track | Horizontal and resultant lower limbs |
| R. V. Breed and Young (2003) | Grab, track, swing | Horizontal upper and lower limbs |
| Vilas-Boas et al. (2003) | Grab and track | Horizontal, vertical lower limbs |
| Benjanuvatra *et al.* (2004) | Grab and track | Horizontal and vertical lower limbs |
| Kibele *et al.* (2008) | Ventral | Horizontal, vertical and resultant |
| Arellano *et al.* (2005) | Grab | Horizontal and vertical lower limbs |
| Mason et al. (2007) | Grab | Horizontal lower limbs |
| Hohmann, Fehr, Kirsten, and Krueger (2008) | Backstroke | Horizontal and vertical lower limbs |
| Galbraith et al. (2008) | Track and one handed track | Horizontal lower and vertical upper and lower limbs |
| Vint, Mclean, Hinrichs, Riewald, and Mason (2009) | Track | Horizontal upper limbs |
| de Jesus *et al.* (2010) | Backstroke | Horizontal lower limbs |
| Vantorre et al. (2010b) | Grab | Horizontal and vertical lower limbs |
| T. Takeda et al. (2010) | Relay | Horizontal lower limbs |
| Cossor, Slawson, Shillabeer, Conway, and West (2011) | Track | Horizontal and vertical lower limbs |
| K. de Jesus, de Jesus, K., Figueiredo, P., Gonçalves, P., Pereira, S. M., Vilas-Boas, J.P., Fernandes, R.J. (2011) | Backstroke | Horizontal lower and upper limbs |
| Kilduff et al. (2011) | Ventral | Horizontal and vertical lower limbs |
| S. E. Slawson et al. (2011) | Track | Horizontal and vertical lower limbs |
| K. E. Honda, Sinclair, Mason, and Pease (2012) | Track and kick | Horizontal vertical and resultant, vertical upper limbs |
| Karla de Jesus et al. (2013) | Backstroke | Horizontal lower and upper limbs |
| S. Slawson, Conway, P., Cossor, J., Chakravorti, N., West, A. (2013) | Kick | Horizontal and vertical lower limbs |

From the overall included studies, 82.14% analyzed the individual ventral starts, followed by 14.28% aiming at backstroke starts, and only 3.57% at relay starts. Twenty-five per cent from the overall ventral starting studies measured the external horizontal and vertical forces reacting on the swimmer's hands.

Researchers have instrumented the handgrips with load cells or bonded strain gauges directly to the hands bar to measure the overall upper limbs force. To measure the horizontal and resultant lower limbs external kinetics at backstroke starting, researchers have used one force plate, while for ventral starts one and two force plates have been mounted over the starting block to measure mainly the horizontal and vertical reaction force components. Despite most of the research groups have used three-dimensional sensors, only two have studied the lateral force component action on the swimmers' lower limbs. Moments of force and centre of pressure were assessed once at individual ventral start.

## Discussion

The external force assessments during swimming starts are considered of great value for coaches and swimmers, since they provide information about how swimmers' movements are generated to propel themselves out of the starting block. The findings of this study evidence that swimming researchers have been very concerned about the external kinetics assessment at individual ventral starts, and have optimized the devices according to the starting rule changes for block configuration (FINA, 2009). However, much effort should be invested to the study of the upper limbs dynamometry, mainly considering all the possibilities allowed by the FINA regulations, as performed by Vint et al. (2009) with instrumented front and side handgrips. Researchers should also consider the implementation of force sensors in lateral handgrips to produce knowledge about the dynamometric profile used at the tuck starting technique.

In contrast to the substantial quantity of studies which approach kinetics at individual ventral starts, there is a paucity of backstroke start kinetic data, mainly due to the technical difficulties associated with the adaptation of the kinetic devices to the starting block and pool wall (Karla de Jesus et al., 2013; K. de Jesus, de Jesus, K., Figueiredo, P., Gonçalves, P., Pereira, S. M., Vilas-Boas, J.P., Fernandes, R.J., 2011). Despite the considerable contribution provided by the previous studies, a large effort should be invested to adapt the kinetic devices according to the actual starting block configuration, as implementing the two horizontal and lateral backstroke start handgrips. Considering the individual

ventral and dorsal starts, the relay techniques have received much less attention, since only one research group has attempted to analyze the horizontal ground reaction force component in three different techniques (T. Takeda et al., 2010). Further research should be conducted including the rear back plate to verify if swimmers change the respective force profiles when performing relay starts using this recently allowed device.

The consistent use of three dimensional force sensors has been implemented mainly to study the horizontal (anterior-posterior) and vertical upper and lower limbs force components. In fact, the major and relevant components are the forces applied in the vertical and antero-posterior axes (S. Slawson, Conway, P., Cossor, J., Chakravorti, N., West, A. , 2013); however, the medio-lateral axis was studied by Vantorre et al. (2010b) in elite and trained swimmers, and might be considered an important feedback parameter to improve technique and performance of young swimmers.

## Conclusion

The external forces assessment during starts is an important concern of the swimming research community. Researchers have continually adapted the instrumented starting block to measure upper and lower limbs forces, mainly at individual ventral starts. However, sports biomechanics and engineers should invest effort to develop a 3D kinetic system based on the actual block configuration capable to identify the upper and lower limbs contribution to propel starters out of the block/wall at different starting techniques.

## Acknowledgments

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## References


Arellano, R., Llana, S., Tella, V., Morales, E., & Mercade, J. (2008). *A comparison CMJ, simulated and swimming grab-start force recordings and their relationships with the start performance.* Paper presented at the ISBS-Conference Proceedings Archive.

Benjanuvatra, N., LytUe, A., Blanksby, B., & Larkin, D. (2004). Force development profile of the lower limbs in the grab and track start in swimming. *Analysis, 14606*(151), 94.

Breed, R. V., & Young, W. B. (2003). The effect of a resistance training programme on the grab, track and swing starts in swimming. *Journal of Sports Sciences, 21*(3), 213-220.

Cavanagh, P., Palmgren, J., & Kerr, B. (1975). A device to measure forces at the hands during the grab start. *Swimming II, International series of sport science*, 43-50.

Cossor, J., Slawson, S., Shillabeer, B., Conway, P., & West, A. (2011). *Are land tests a good predictor of swim start performance?* Paper presented at the ISBS-Conference Proceedings Archive.

de Jesus, K., de Jesus, K., Figueiredo, P., Gonçalves, P., Pereira, S. M., Vilas-Boas, J. P., & Fernandes, R. J. (2013). Backstroke start kinematic and kinetic changes due to different feet positioning. *Journal of Sports Sciences, 31*(15), 1665-1675.

de Jesus, K., de Jesus, K., Figueiredo, P., Gonçalves, P., Pereira, S. M., Vilas-Boas, J.P., Fernandes, R.J. (2011). Biomechanical analysis of backstroke swimming starts. *Int. J. of Sports Med., 32*, 546-551.

Elliott, G. M., Sinclair, H. . (1971). The influence of block angle on swimming sprint starts. *In L. Lewillie, J.P. Clarys (Eds.), Biomechanics*, 183-189.

FINA. (2009). Fedération Internationale de Natation. Facilities Rules. http://www.fina.org Retrieved 12 September, 2014

Galbraith, H., Scurr, J., Hencken, C., Wood, L., & Graham-Smith, P. (2008). Biomechanical comparison of the track start and the modified one-handed track start in competitive swimming: An intervention study. *Journal of applied biomechanics, 24*(4), 307-315.

Hay, J., Guimaraes, A., & Grimston, S. (1983). A quantitative look at swimming biomechanics. *Swimming technique, 20*(2), 11-17.

Hohmann, A., Fehr, U., Kirsten, R., & Krueger, T. (2008). Biomechanical analysis of the backstroke start technique in swimming. (2), 28-33.

Honda, K. E., Sinclair, P. J., Mason, B. R., & Pease, D. L. (2012). *The effect of starting position on elite swim start performance using an angled kick plate.* Paper presented at the International Society of Biomechanics in Sports.

Kibele, A., Siekmann, T., & Ungerechts, B. (2008). *A biomechanical evaluation of dive start performance in swimming-force development characteristics and angular momentum,.* Paper presented at the ISBS-Conference Proceedings Archive.

Kilduff, L. P., Cunningham, D. J., Owen, N. J., West, D. J., Bracken, R. M., & Cook, C. J. (2011). Effect of postactivation potentiation on swimming starts in international sprint swimmers. *The Journal of Strength & Conditioning Research, 25*(9), 2418-2423.

Krüger, T., Wick, D., Hohmann, A., El-Bahrawi, M., & Koth, A. (2003). *Biomechanics of the grab and track start technique.* Paper presented at the Proceeding of the IX International Symposium on Biomechanics and Medicine in Swimming.—France: University of Saint-Etienne.

Mason, B., Alcock, A., & Fowlie, J. (2007). *A kinetic analysis and recommendations for elite swimmers performing the sprint start.* Paper presented at the ISBS-Conference Proceedings Archive.

Mason, B., Mackintosh, C., & Pease, D. (2012). *The development of an analysis system to assist in the correction of inefficiencies in starts and turns for elite competitive swimming.* Paper presented at the ISBS-Conference Proceedings Archive, Melbourne: Australian Catholic University.

Naemi, R., Arshi, A., Ahadian, A., & Barjasteh, B. (2001). *3d kinematic and kinetic analyses of two methods for grab start technique.* Paper presented at the ISBS-Conference Proceedings Archive (XXIX).

Shierman, G. (1978). Stability in competitive swimming starts. *Swimming Techniques, 14*, 117-118.

Slawson, S., Conway, P., Cossor, J., Chakravorti, N., West, A. . (2013). The categorisation of swimming start performance with reference to force generation on the main block and footrest components of the Omega OSB11 start blocks. *Journal of Sports Sciences, 31*, 468 - 478.

Slawson, S. E., Conway, P. P., Cossor, J., Chakravorti, N., Le-Sage, T., & West, A. A. (2011). The effect of start block configuration and swimmer kinematics on starting performance in elite swimmers using the Omega OSB11 block. *Procedia Engineering, 13*, 141-147.

Stevenson, J. R., & Morehouse, C. A. (1979). *Influence of Starting-Block Angle on the Grab Start in Competitive Swimming.* Paper presented at the Swimming III.

Takeda, T., Takagi, H., & Tsubakimoto, S. (2010). *Comparison among three types of relay starts in competitive.* Paper presented at the Biomechanics and Medicine in Swimming XI.

Vantorre, J., Seifert, L., Fernandes, R., Vilas-Boas, J., & Chollet, D. (2010a). Kinematical profiling of the front crawl start. *International journal of sports medicine, 31*(01), 16-21.

Vantorre, J., Seifert, L., Fernandes, R., Vilas Boas, J., & Chollet, D. (2010b). Comparison of grab start between elite and trained swimmers. *International journal of sports medicine, 31*(12), 887-893.

Vilas-Boas, J. P., Cruz, J., Sousa, F., Conceicao, F., Fernandes, R., & Carvalho, J. (2003). *Biomechanical analysis of ventral swimming starts: Comparison of the grab start with two track-start techniques.* Paper presented at the Biomechanics and Medicine in Swimming IX, Saint-Étienne, France.

Vilas-Boas, J. P., Cruz, M. J., Sousa, F., Conceição, F., & Carvalho, M. J. (2000). *Integrated kinematic and dynamic analysis of two track-start techniques.* Paper presented at the ISBS-Conference Proceedings Archive (XVIII).

Vint, P., Mclean, S., Hinrichs, R., Riewald, S., & Mason, R. (2009). *Effects of handle and block configuration on swim start performance.* Paper presented at the ISBS-Conference Proceedings Archive (XXVII).

Zatsiorsky, V., Bulgakova, N. Z., & Chaplinsky, N. (1979). *Biomechanical analysis of starting techniques in swimming*.

# Chapter 3.

**Development of a new dynamometrical station for swimming start performance analysis.**

Literature survey suggested that a dedicated dynamometrical assembly, full instrumented starting block, is needed for the measurement of forces produced by each limb during both individual and changeover ventral swimming starts. The same was also concluded for the backstroke starts, but those fall out of the aims of this thesis. Indeed, no solution is known allowing this kind of assessment on all the up to date proposed, described and used starting techniques (Figure 1).

This chapter aims to describe the design and implementation techniques used towards a prototype implementation for full dynamometric assessment of solid contact forces during swimming events. This means that it was conceived as a system with extended capabilities in order to receive dynamometric data from backstroke start instrumented hand grips and feet supporting underwater force platform devices.

The chapter 3.1 provides the background needed for the implementation of the load sensor prototype, while the chapter 3.2 fits the acquired knowledge in the implementation of the full dynamometric device prototype.

***This chapter is required to be publication reserved on account of the intention of patent***. (NPAT 212/14 and INPI nº 108229)

## Chapter 3.1

**Design and construction of a 3D force plate prototype for developing an instrumented swimming start block**

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**Abstract**

In competitive swimming external tridimensional forces assessment is crucial to improve starting technique performance. This work aimed to describe the design and construction of a tridimensional force plate prototype, which might be a modular sensor of an instrumented swimming starting block. For this purpose four

steps were followed: (i) numerical determination of sensor conspicuous spatial positioning; (ii) development of a first test device and respective calibration procedures; (iii) final prototype (3D force plate) development and implementation; and (iv) development and programming of a high speed multiple data acquisition system. Vertical force (< 140 N ± 5%) and centre of pressure real time determination (± 3% to centre distance uncertainty) are compliant with literature data and horizontal force is assessed based on centre of pressure displacement time derivatives. The software for data acquisition and interpretation was developed leading to calibration procedure providing a set of gains for sequential balance protocol and final transfer matrix. Although the final prototype implementation was the concerning issue, this prototype also has proven to be an important milestone for a dynamometric swimming start block development.

**Keywords:** Instrumentation, Kinetics, Ground Reaction Forces, Swimming.

## Introduction

Human locomotion is intrinsically connected to developed ground reaction forces (Cappello, Bagalà, Cedraro, & Chiari, 2011). In swimming individual and relay starts, this contact is restricted to the block phase (S. Slawson, Conway, P., Cossor, J., Chakravorti, N., West, A. , 2013), with the corresponding external forces being analyzed since the Elliot and Sinclair's pioneer instrumented block (Elliott, 1971). Currently, coaching and commercial instrumentation are still lacking some of final solutions and important features (Luis Mourão et al., 2014) inspiring new biomechanical research directions. For instance, it is well known that the external kinetic analysis is crucial to determine the parameters that influence the different starting technique performances (Luis Mourão et al., 2014; S. Slawson, Conway, P., Cossor, J., Chakravorti, N., West, A. , 2013) and that previous ventral start related studies have recommended that elite swimmers should work towards producing high levels of peak force resulting in better ventral start performance (S. Slawson, Conway, P., Cossor, J., Chakravorti, N., West, A. , 2013).

For start optimization, if a limb is in contact to a force platform, the respective tridimensional (3D) force $\vec{F}$ and moment of force $\vec{M}$ should be measured, as good sports practice recommend (S. Slawson, Conway, P., Cossor, J., Chakravorti, N., West, A. , 2013). Each of the two vectors are 3D and have to be decomposed in three Cartesian components $\vec{F} = \left(F_x, F_y, F_z\right)$ and $\vec{M} = \left(M_x, M_y, M_z\right)$ with $x$, $y$ and $z$ framed according to the International Society of Biomechanics (ISB) (Wu et al., 2002). The $\vec{F}$ vector components are due to swimmer's weight and dynamic effects (Luis Mourão et al., 2014) and the respective reaction is a symmetrical propulsive 3D quantity (according to Newton's action-reaction third law). The $\vec{M}$ measurement is used for assessing contact position – the centre of pressure (COP). Hence, it is possible to obtain the 3D force time history (available after calibration and zero adjustment operations) and the COP migration, requiring the topology of the contact surface to correct its assessment.

Ground reaction force (GRF) effect in the swimmers' starting movements can be computed if considering it applied to the body with known centre of mass (CM), weight and inertia matrix. Such force and moment of force can be appropriately time integrated to provide impulse and velocity (if the swimmers' mass is known) or displacement (by double time integration). In addition, the $\vec{M}$ measured at each contact point allows locating the COP of each limb, which can also evidence postural effects (Browne & O'Hare, 2000; L Mourão et al., 2015). As to perform this measurement a tailored platform set is needed, a new structure suitable for swimming start performance assessment should be developed, it should be designed and instrumented to obtain a bundle of signals, giving full information concerning the exerted force (including its COP). After a proper calibration, this device could also be used in day to day biomechanical evaluation procedures as a force platform (Walicka-Cupryś et al., 2014) or even for gait (Roesler, Haupenthal, Schütz, & de Souza, 2006) and jump analysis (Walsh, Ford, Bangen, Myer, & Hewett, 2006)(Walsh *et al.*, 2006).

Force platforms are devices used for force evaluation through performed measurements on structures in contact to limbs (Collins, Adamczyk, Ferris, & Kuo, 2009). These measurements can be carried out with strain gauges (Karla

de Jesus et al., 2013), piezoelectric devices (S. Slawson, Conway, P., Cossor, J., Chakravorti, N., West, A. , 2013) or with fiber optic sensors (Pinto & Lopez-Amo, 2012). Strain gauges, present relevant advantages over piezoelectric sensors (such as a better stability for long-term measurements, providing absolute measurements instead of relative ones, while piezoelectric sensors require a specific signal conditioning device known as a charge amplifier (Roriz, Carvalho, Frazão, Santos, & Simões, 2014). The strain gauge is bonded on the surface of a mechanical structure whose geometry definition, among several sensor topologies that have been used (Bracci, Reinhorn, & Mander, 1992; Cavanagh et al., 1975; O'Driscoll, Stanley, & Little, 2013) impacts in the force plate project and the final selected topology should be based on simplicity and robustness criteria.

An instrumented swimming start block should assess swimmer's limbs forces produced in all existent start techniques and respective variants. Current devices for force measurement applications in swimming starts (and turns) are, though, unable to alllow some signal separation and avoid crosstalk (*cf.* Luis Mourão et al. (2014) for a review on the topic). For example, S. Slawson, Conway, P., Cossor, J., Chakravorti, N., West, A. (2013) used two sagittal aligned platforms dedicated to track start characterization, not allowing laterality contribution apartness in the grab start. Cavanagh et al. (1975) and (Galbraith et al., 2008) assessed force produced by the hands simultaneously in mixed kinetics (splitting the individual hands force contribution apart was impossible, once again). Thus, the high replication number forecast to cover all above mentioned possibilities implies a careful load cell choice as cost could rise excessively. The current work aimed to design and construct a low cost 3D force plate prototype composed by a hollow pipe topology and simple anchorage. This force plate, reproduced in a certain amount of times, would map completely the limbs reaction force produced in swimming starts allowing more objective and reliable coach feedback.

## Materials and Methods

*Definition of measurement premises and calibration*

The force plates design has initiated using CAD (3D CAD, DS Solidworks, Dassault Systèmes S.A., France) to define prototype geometry. Following Bracci et al. (1992) and Esser et al. (2013) design, an aluminum cylindrical shell (pipe) load cell (complying with known mechanical properties, *e.g.*, Young modulus and Poisson ratio consistent with the project requirements and the appropriated strain gauges selected) was chosen (Figure 4, A panel), which was consistent with the necessary stiffness and estimated load amplitude. Modelling the conspicuous positioning of the sensors was defined as thoroughly as possible. Nevertheless, some constraints had to be addressed, particularly the establishment of a preferential vertical force direction (using a 1000 N vertical force load) and the COP locus of the respective force vector. Such locus was defined as the top plane and materialized on the top cap surface (Figure 4, B panel). Due to symmetry, only a squared quarter of the available area was used in the simulation. Moreover, the test device resonance frequency and the strain-simulated signals (Figure 4, C panel) were obtained by numerical methods using ANSYS 14.0 software (ANSYS® Workbench™ 2.0 Dassault Systems, France).

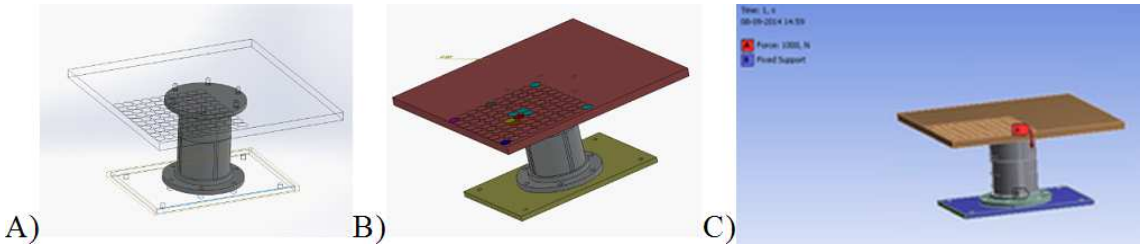



*Figure 4 Load cell design approach to simulated operation: A) Perspective of the Load Cell main component; B) Target areas for force application; C) Exemplar border vertical force of 1000 N for simulation.*

Calibration algorithms were developed to transfer functions assessment, focused on matrices applied to all signals obtained from sensors, to provide object dynamical force-moment behaviour. The main algorithm was based in a signal normalization obtained with a central positioned vertical force (linearizing the main transfer function of each sensor for the exactly same strain signal, resulting from symmetry). The main transfer function for vertical force measurement is given by the following equation:

$$F_z = \frac{1}{4}\left(A_1\varepsilon_1 + A_2\varepsilon_2 + A_3\varepsilon_3 + A_4\varepsilon_4\right) \quad (1)$$

Where $A_1, A_2, A_3, A_4$ are the gain-calibration parameters to provide strain to force ratio (N/με), the paired $\varepsilon_1, \varepsilon_2\ (\mu\varepsilon)$ are the strain outcome and sensor positioning (respectively) defining the $x$ axis or lateral direction, the $\varepsilon_3, \varepsilon_4\ (\mu\varepsilon)$ is the pair sensor positioning that defines $y$ axis or horizontal direction and $F_z$ is the vertical reaction to the vertical force applied. If a mismatch of the cover centre is produced, modifying the COP of the resulting applied force, the imbalance obtained between opposite sensors reveals its coordinates according to the following pair of equations:

$$\begin{cases} x_{CoP} = \dfrac{h \cdot F_x - M_y}{F_z} \\ y_{CoP} = \dfrac{h \cdot F_y + M_x}{F_z} \end{cases} \quad (2)$$

Where $M_x$ and $M_y\ (N \cdot m)$ are $x$ and $y$ torque components, $F_x$ and $F_y\ (N)$ are $x$ and $y$ force components, $h\,(m)$ is the height of the top platform cover plane to strain-gauge sensor vertical distance and $x_{COP}$ and $y_{COP}\ (m)$ are COP coordinates in a frame on the cover plane (centred at mid distance of the four sensors) with $x$ and $y$ axis previously defined. Moment assessment and COP determination can be obtained, in practice, according to the following pair of equations (which are variants of Equations 2):

$$\begin{cases} x_{CoP} = \dfrac{IE}{W\varnothing}\left(A_1\varepsilon_1 - A_2\varepsilon_2\right) \\ y_{CoP} = \dfrac{IE}{W\varnothing}\left(A_3\varepsilon_3 - A_4\varepsilon_4\right) \end{cases} \quad (3)$$

Where $I = \frac{\pi}{64}\left(\varnothing_{ext}^{4} - \varnothing_{int}^{4}\right)$ $\left(m^4\right)$ is the axial inertia momenta around the centre of the load cell tube (with $\varnothing_{ext}$ $(m)$ as the external diameter and $\varnothing_{int}$ $(m)$ as the internal diameter), $E = 7.1 \cdot 10^{10}\, Pa$ is the pipe aluminium Young modulus, $W$ $(N)$ is the weight applied (or $F_z$) and $\varnothing$ $(m)$ is the tube diameter (the external diameter was assumed due to the small thickness of the tube wall).

At last, with the position of COP, it is possible to assess force $F_x$ and $F_y$ $(N)$ components, as the following equations (4) state.

$$\begin{cases} F_x = m\dfrac{d^2\left(x_{COP}\right)}{dt^2} \\ F_y = m\dfrac{d^2\left(y_{COP}\right)}{dt^2} \end{cases} \tag{4}$$

Where $m$ $(kg)$ is the mass of the body and $\frac{d^2\left(x_{COP}\right)}{dt^2}$ , $\frac{d^2\left(y_{COP}\right)}{dt^2}$ $\left(m \cdot s^{-2}\right)$ are the COP position second time derivative or acceleration on cover plane components. However, these values are limited to contact area (a $1kg$ pendulum with $3kg$ base has been used for test) and are also dependent on the sampling rate, demanding a low noise data acquisition system for reliable values if numerical differentiation is used.

*Development of a first test device and respective calibration procedures*

Following the earlier mentioned simulations, the test device was designed, assembled and instrumented with four strain-gages of $120\Omega$ 1-LY41-6/120, Self-Temperature-Compensation Gages, (HBM, Darmstad, Germany). The strain gages were configured as four ¼ Wheatstone bridge circuit for axial strain

measurements, whose bridge topology allows the measurement of the independent strain in each sensor loci due to different force application points or COP locus assessment. No temperature compensation was applied, as manufacturer claims that the strain gauges were quite insensitive to $1.8\mu m/m/°C$ or $\mu\varepsilon/°C$ in a temperature range of $10$ to $80°C$.

Four strain-gauges were bonded to the cylindrical tube as depicted in Figure 5, A panel, where it is exhibited the strain-gauge loci in the middle of the outside tube generatrix with the final implementation being shown in Figure 5 B panel.

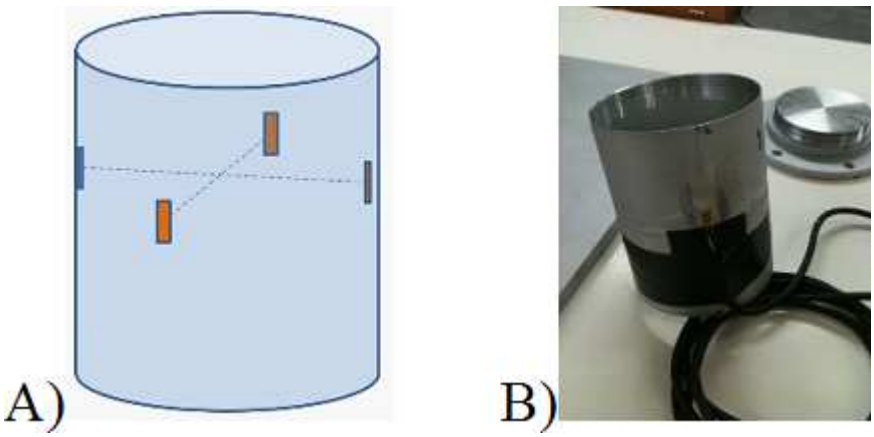



*Figure 5 Load Cell implementation: A) Perspective of the strain-gauge loci; B) Perspective of the strain-gauge bonded in the load cell.*

For strain data acquisition the equipment used was a NI SCXI-1001 Chassis with NI SCXI-1520 8-Channel Universal Strain Gage Input Module connected to NI SCXI-1314 Front-Mounting Terminal Block (National Instruments Corporation, USA).

The force calibration procedure involved a set of eight cylindrical lead masses of about $10kg$ (each mass had $245mm$ diameter x $15mm$ height). A $0.2kg$ stainless steel cylindrical pin support, with $20mm$ diameter x $40mm$ height (representing a contact area less than $5\%$ of the platform cover area) was attached to a convenient weight insertion cavity. It was intended to apply forces perpendicular to the platform cover, which was horizontally placed. To calibrate vertical forces, the pin was centred in the middle of the platform cover and increasing values of weight were applied. The linearization of such data samples led to the transfer function of the vertical force that, for centred vertical force measurement, is given

by Equation 3, providing solutions for the linear regressions in the following equations:

$$A_1\varepsilon_1 = A_2\varepsilon_2 = A_3\varepsilon_3 = A_4\varepsilon_4 \qquad (5)$$

The calibration setup for vertical central force and for moment of force determination is depicted in Figure 6, A panel. To perform the moment of force calibration the weight set was positioned decentred in eight equal displacements along each bisector line of the platform square cover borderlines. A small lifting bridge was constructed for load positioning, which gave rise to the same vertical forces but different moments. Hence, nine points of output imbalance signals occurred between pairs of opposite strain-gauges, particularly in opposite to the centre and in the line of load displacement (Figure 6, B panel). This procedure was repeated throughout the other perpendicular direction and data collected were linearized. Data collected from the 18 load positions was used to obtain COP coordinates from the imbalance values.

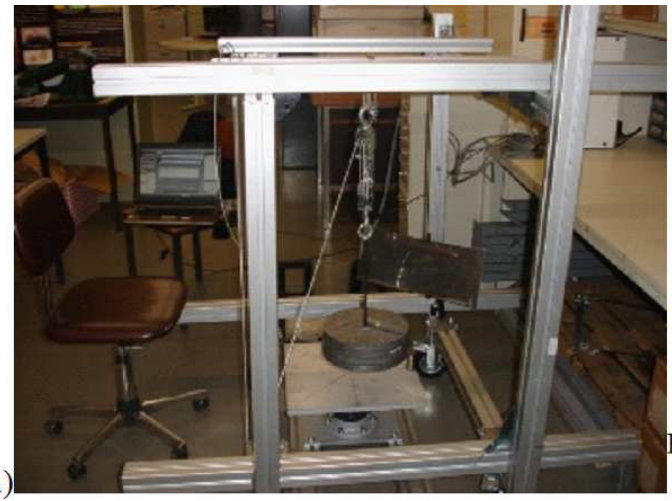
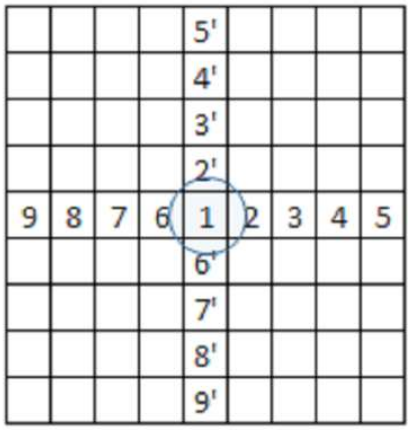
A)  B) 


*Figure 6 – Calibration setup: A). Setup for lifting and positioning of force application points; B) Centred force locus is identified by circular area and COP displacement scheme for moment of force calibration is identified by squared ordinals.*

*Development and implementation of the final prototype*

As the test device, the final prototype was assembled and instrumented, bonding four strain-gages of 350Ω ©HBM (SGT-1/350-TY11, Self-Temperature-Compensation Gages, ©HBM, Darmstad, Germany) in a four ¼ Wheatstone

bridge topology circuit for strain measurements. Differently from the earlier test device, it was selected a category of strain gauges with greater resistance, reducing the power dissipation since the pipe was 90% thinner. Similarly to earlier test device, no temperature compensation was applied and the strain sensitivity was the same.

The four strain-gages were bonded axially to the tube selected for the final prototype: a thin walled cylindrical shell $0.1mm$ thickness, made by aluminum metal (Figure 4, A and B panel), as it was an adapted regular beverage can, sealed for stability purposes. The same topology, electrical and position constraints of the first device test (Figure 5, A panel) were applied for force and moment of force determination.

Measuring data were collected with a suitable four channel NI 9237 acquisition board, which was connected to NI USB 9162 module, both from NI (National Instruments Corporation, USA). Both devices ensured simultaneous acquisition data in up to four strain data channels (2000 sample/s sample rate) and matched the measurement requirements. The final bonded sensors loci and apparatus are depicted in Figure 7 A and B panels, respectively. Calibration procedure was reproduced following the same procedure of the first test device case (Figure 6, B panel), but the weight applied was about $10\%$ lower ($<140N$ range) and the lift bridge was discarded.

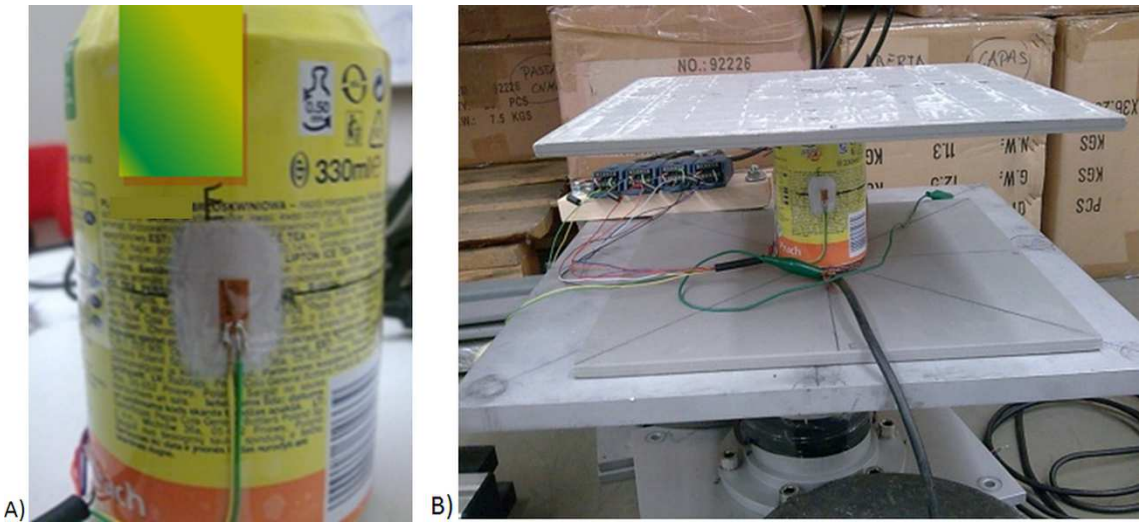



*Figure 7 Strain gages positioning and platform assembly: A). Sensor element of the force plate; B). Full structure.*

*Development and programming of high speed multiple data acquisition*

The last step was the implementation and programming of high speed multiple acquisition software. The implemented algorithms have included mainly linear regressions and the outcomes were the resulting individual strain-gauge gains $A_1, A_2, A_3, A_4$. Total addictive contribution of each individual strain gauge signal gives the equivalent central force to be measured, as in Equation (3). Moment of force linearization was applied and the transfer function was implemented following the Equations (4). Such implementation used suitable dedicated LabVIEW® (National Instruments Corporation, USA) routine for data storage and presentation. A routine for COP locus assessment and parallel to plane force components $F_x$ and $F_y$ estimation was included.

## Results

Both in the first test device and in the final prototype , the evidence of a large area where strain is well defined and maximal values are reached, exhibits the place where strain-gauge should be bonded (Figure 8). High value resonance frequency modes were achieved (above $200Hz$) in both solutions.

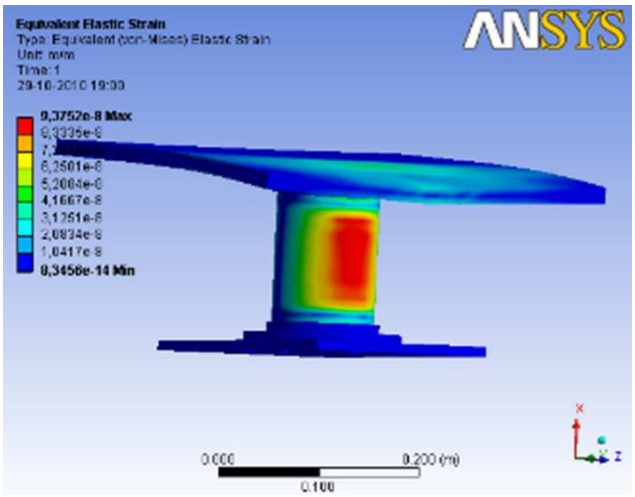



*Figure 8 Strain pattern in a border weight positioning of 1000 N.*

Figure 9 represents the double linearization in force-moment of force (in normalized strain measures) while the weight COP is positioned in each of the points depicted in Figure 3, B panel applied in the final prototype platform cover. The constant values of the vertical force (in cyan) can be seen in this figure, while regular displacements provide also regular linear increase/decrease of the strain signal combined. The adding of the four calibrated and normalized signals provides the vertical force value and the opposite sensor signal subtraction leads to the on cover plate COP displacement measurement.

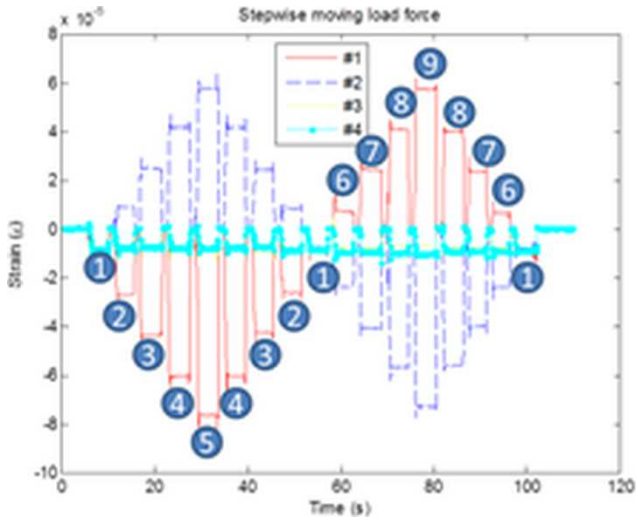



*Figure 9 Calibration data in normalized strain produced in each positioning for a weight of 42 N.*

Values of the gains for the developed final prototype ranging between $1.365085 \cdot 10^6 N/\varepsilon$ and $1.691198 \cdot 10^6 N/\varepsilon$ for the applied central force. Such gains provide an overall uncertainty in the vertical force of about $0.5N$. An upgrade in the software has included numerical differentiation tools that, applied to COP positioning, led to acceleration tangential to plane of platform body with components $a_x$ and $a_y$. Tangential to force plate cover plane, $F_x$ and $F_y$ components (Figure 10) are derived from weight and those acceleration components allowing to finally assessing the 3D force vector.

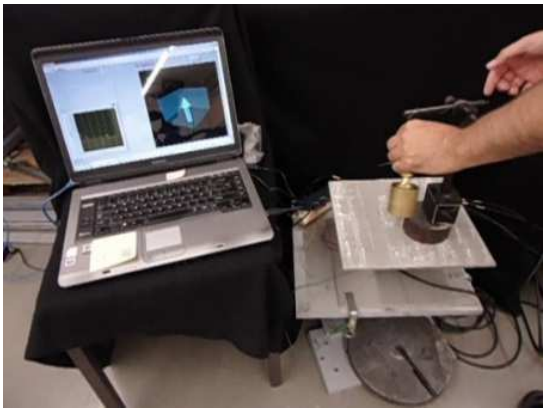


*Figure 10 LabVIEW® interface and setup for straightforward results presentation with a pendulum dynamic load.*

## Discussion

Due to current FINA's (Fédération Internationale de Natation) facility rules starting and facility rule modifications, some research groups developed new technologies to measure the external forces applied to the swimming starting block in different starting techniques (Cavanagh et al., 1975; Collins et al., 2009). In addition, researchers have also evolved their study purposes to separate the effective swimmers' forces from the inertial effects (Luis Mourão et al., 2014), highlighting the crucial role of the instrumented starting block in swimming performance studies. This work aimed to describe the design and construction of a low-cost force platform final prototype, as precursor of a swimming suitable dynamometric device for different start technique evaluation. The implementation of such platform displayed low vertical force range ($<140N$), high sensitiveness ($\sim 0.5N$), 3D extrapolation and short implementation budget suitable for a modular solution involving several force platforms.

Platform design followed the cylindrical geometry used by Bracci et al. (1992) and Esser et al. (2013) has showed how a very simple topology would be suitable for 3D measurement purposes. Furthermore, such simple geometry proposal is characterized by a shorter budget compared with the commercial devices (S. Slawson, Conway, P., Cossor, J., Chakravorti, N., West, A. , 2013) that provide direct COP assessment together with parallel to cover force measurements (i.e., not in function of COP displacement). The current topology determines the acceptance of measurements based on extrapolations turning COP position assessment with an uncertainty proportional to centre distance ($\sim 3\%$) compared

to more elaborated topologies. This uncertainty growth and the obtained distribution exhibit a minimum value in the centre of the platform cover, in agreement with Collins et al. (2009). Such difficulty can be overcome by the use of redundancy (reproducing the 3D load cell and locating four of them in the corners, based on Walsh et al. (2006), or by changing the topology of the load cell as in Walicka-Cupryś et al. (2014)). The error has been compatible with the topology proposed before Walicka-Cupryś et al. (2014), while the resonance frequency of the first test device has been found three times greater. However, the force range of the current final prototype is lower than Roesler et al. (2006), as the thin pipe wall limits the applied load.

Accurate measurements of ground reaction forces from force plates are important in many areas of biomechanical research (L Mourão et al., 2015; Walicka-Cupryś et al., 2014). In the current study, force platform design and linearization algorithms have shown to be suitable to force and moment of force assessment (cf. Figure 6). In fact, the present 3D force plate prototype displayed a very regular and bilinear behaviour to both vertical force and moment of applied force, as presented before (Roesler et al., 2006). In opposition to the current study that measured directly uniaxial forces although decentred the referred authors used calibration procedures that led to COP definition with small uncertainty. The revealed uncertainty in the current force plate is higher due to its extrapolation measurement nature. In competitive swimming, the moment of force have not been often assessed in different swimming start techniques. However, the moment of force is intrinsically connected to COP assessment leading to postural effects that intervene in swimming start performance (Luis Mourão et al., 2014; Wu et al., 2002), emphasizing its importance.

Notwithstanding the relevance of current data, some study's limitations should be considered. For strain measurement using strain gage connected in Wheatstone full bridge arrangement at least four wires are needed (two for excitation and two for measurement), which is twice the required for piezoelectric sensors. With a ¼ Wheatstone bridge it is necessary two or three wires (in this case it is possible to assess wire resistance), but the strain signal reduces to a quarter of the full bridge measured. However, the strain gage sensor represents a highly tested, mature and overspread technology, offering good sensitivity, precise measurements and

competitive price (Karla de Jesus et al., 2013). In addition, noise patterns and high sensitivity to moment of force in large COP displacements advise the use of more than one load cell tube (Browne & O'Hare, 2000), as this is due to the central extrapolation nature of the measurement accomplished with this type of single load cell. With four platform cap cover corner positioned load cells, central COP would be determined with much less uncertainty, as previously mentioned (Bracci et al., 1992). Such new topology, although more expensive, would forecast a minimum centred to cover COP determination uncertainty. However, the first topology cost is incomparably low budget as about 50 € (data acquisition system not included that, however, could be shrunk with some electronics and microcontroller excitation/data acquisition board). Another geometrical sensor loci apparatus possibility would be to apply Roesler et al. (2006) topology, which is uncertainty compatible with Bobbert and Schamhardt (1990).

Despite the above mentioned advantages of the final prototype, which is suitable for force and moment of force measurements, it is recognized that in different start techniques swimmers contact with soil limb postures and loci are variable, weakening the information of a single platform. As swimmers' limbs generate propulsive force, it is required an integer minimum number of platforms for physical conditions general mapping. In addition, the environment of the swimming pool demands water proof sensors (as the bonding process is hygroscopic and may be damaged). Finally it is expectable to have a regular instrumented block complying with FINA's rules (FR 2.7 and 2.10), designing the loci and anchorage of the necessary set of platforms. Such dynamometric device would be available simultaneously for scientific investigation and for coaching purposes, overcoming the limitations depicted in the commercial instrumented starting blocks available (S. Slawson, Conway, P., Cossor, J., Chakravorti, N., West, A. , 2013). According to Walsh et al. (2006), one limitation for the use of force plate in training is that they are typically heavy, enhancing the wall mount of the set of platforms and their mechanical fixation importance, which, in turn, should prevent any crosstalk measurement between platforms (as their sensitivity is high). Future studies should take into account of such feature and try to mitigate its effect.

## Conclusion

A device which can be considered the precursor of the next homemade load cell generation has been developed for swimming start performance studies. The device has accomplished the main purpose of vertical force and COP locus determination. It has also measured the horizontal force providing that its assessment could be calculated by COP displacement, albeit the results assessed have proven to be more uncertain the more off-centre COP of force applied. The main influence has arisen from the central extrapolation nature of the load cell or final prototype but, as this work has also shown, a low-cost force plate design could be the core of a more vast assembly, reproducing the final prototype a certain amount of times and in combination of other requirements (mechanical, biomechanical and electronics). This device, as a stand-alone solution, could be used to perform measurements in didactical situations, if the precision requirements could be relaxed. Further studies, following final prototype development branch and, in parallel, the biomechanics boundary conditions involved in the swimming starts, should be carried out to develop a general purpose instrumented swimming start block.

Acknowledgments

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## REFERENCES


Bobbert, M. F., & Schamhardt, H. C. (1990). Accuracy of determining the point of force application with piezoelectric force plates. *Journal of Biomechanics, 23*(7), 705-710.

Bracci, J. M., Reinhorn, A. M., & Mander, J. B. (1992). Seismic resistance of reinforced concrete frame structures designed only for gravity loads: Part I-Design and properties of a one-third scale model structure. *Technical Rep. No. NCEER-92, 27*.

Browne, J., & O'Hare, N. (2000). A quality control procedure for force platforms. *Physiological measurement, 21*(4), 515.

Cappello, A., Bagalà, F., Cedraro, A., & Chiari, L. (2011). Non-linear re-calibration of force platforms. *Gait & Posture, 33*(4), 724-726.

Cavanagh, P., Palmgren, J., & Kerr, B. (1975). A device to measure forces at the hands during the grab start. *Swimming II, International series of sport science*, 43-50.

Collins, S. H., Adamczyk, P. G., Ferris, D. P., & Kuo, A. D. (2009). A simple method for calibrating force plates and force treadmills using an instrumented pole. *Gait & Posture, 29*(1), 59-64.

de Jesus, K., de Jesus, K., Figueiredo, P., Gonçalves, P., Pereira, S. M., Vilas-Boas, J. P., & Fernandes, R. J. (2013). Backstroke start kinematic and kinetic changes due to different feet positioning. *Journal of Sports Sciences, 31*(15), 1665-1675.

Elliott, G. M., Sinclair, H. . (1971). The influence of block angle on swimming sprint starts. *In L. Lewillie, J.P. Clarys (Eds.), Biomechanics*, 183-189.

Esser, S. M., Vlietstra, N. J., Farley, D. P., Medicherla, A., Sokn, S. A., Collins, C. J., . . . Zinn, M. R. (2013). An extramedullary three degree of freedom limb deformity correction device for pediatric applications. *J. Med. Device*, 1-26.

Galbraith, H., Scurr, J., Hencken, C., Wood, L., & Graham-Smith, P. (2008). Biomechanical comparison of the track start and the modified one-handed track start in competitive swimming: An intervention study. *Journal of applied biomechanics, 24*(4), 307-315.

Mourão, L., de Jesus, K., de Jesus, K., Fernandes, R. J., Vaz, M. A., & Vilas-Boas, J. P. (2014). External kinetics in individual and relay swimming starts: a review. *XII International Symposium for Biomechanics and Medicine in Swimming*, 179-184.

Mourão, L., de Jesus, K., Viriato, N., Vilas-Boas, J. P., Monteiro, J., & Vaz, M. A. P. (2015). Design and construction of a 3D force plate prototype for developing an instrumented swimming start block. *Submitted to Journal of Biomedical Engineering and Informatics*.

O'Driscoll, C., Stanley, W., & Little, E. (2013). An Examination of Various Methods of Minimising Strain Gradients in 3D Embedded Strain Gauge Analysis. *Strain, 49*(6), 507-520.

Pinto, A. M., & Lopez-Amo, M. (2012). Photonic crystal fibers for sensing applications. *Journal of Sensors, 2012*, 1-22.

Roesler, H., Haupenthal, A., Schütz, G. R., & de Souza, P. V. (2006). Dynamometric analysis of the maximum force applied in aquatic human gait at 1.3 m of immersion. *Gait & Posture, 24*(4), 412-417.

Roriz, P., Carvalho, L., Frazão, O., Santos, J. L., & Simões, J. A. (2014). From conventional sensors to fibre optic sensors for strain and force

measurements in biomechanics applications: A review. *Journal of Biomechanics, 47*(6), 1251-1261.

Slawson, S., Conway, P., Cossor, J., Chakravorti, N., West, A. . (2013). The categorisation of swimming start performance with reference to force generation on the main block and footrest components of the Omega OSB11 start blocks. *Journal of Sports Sciences, 31*, 468 - 478.

Walicka-Cupryś, K., Przygoda, Ł., Czenczek, E., Truszczyńska, A., Drzał-Grabiec, J., Zbigniew, T., & Tarnowski, A. (2014). Balance assessment in hearing-impaired children. *Research in developmental disabilities, 35*(11), 2728-2734.

Walsh, M. S., Ford, K. R., Bangen, K. J., Myer, G. D., & Hewett, T. E. (2006). The validation of a portable force plate for measuring force-time data during jumping and landing tasks. *The Journal of Strength & Conditioning Research, 20*(4), 730-734.

Wu, G., Siegler, S., Allard, P., Kirtley, C., Leardini, A., Rosenbaum, D., . . . Stokes, I. (2002). ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion-Part I: Ankle, hip, and spine. *Journal of Biomechanics, 35*, 543-548.

## Chapter 3.2

**A novel dynamometric device for four limb forces and moments (3D-6DoF) assessment in swimming starts**

*(Under Patent submission – not publishable)*

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## Abstract

Ground reaction force (GRF) measurement, has been used to assess propulsive force in subjects. The main purpose of this work is to provide a tool to assess the GRF exerted by the swimmer while performing ventral starts characterized by actions of both sides upper and lower limbs. The pathways followed, led to a tool that is able to monitor each limb 3D force as well as limb's Centre of Pressure (COP) in any of the possible ventral start techniques, both for individual and relay events. Moreover, the combination of devices covers the set of possible ventral starts available (described and used), and also should provide an integrated solution while considering backstroke start techniques. The pathways to be considered followed the heuristics on the options available: first the load cell concept and definition; second the selection of the set of starting techniques swimmers' postures to be covered and the overall device envelope concept in order to accomplish the two main targets of this task: without neglecting the individual limb force measurement specificities and FINA's facilities rules fulfilling; the third step is devoted to the hardware and software definition in order to cover all other specific constraints. An effort was invested to define the most universal device covering the most part of the possible combinations of limb positions, with the minimum amount of platforms to be used.

**Keywords:** kinetics, dynamometry, biomechanics, ventral swimming starts, 3D force, centre of pressure

## Introduction

It is known that the 15 m starting performance can differ between elite swimmers by only ~0.40 s (Mason et al., 2012; Seifert, Vantorre, Chollet, Toussaint, & Vilas-Boas, 2010), with decisive effect to the final classification of several competitive events.

As shown in Figure 1, there are a number of ventral start techniques available to be performed by the swimmers, both during individual and relay events, with specific constrains during changeovers. Grab and track start techniques are the most commonly used since long, with some controversial outcomes in literature

regarding their comparative potential for performance. After the 2009 rules change, however, the grab start was almost abandoned, once swimmers and coaches immediately assumed the advantage of the use of the new backplate allowed. Nevertheless, empirical evidences of the new track start advantages remain scarce, despite the seminal study of this technique already pointed in the direction of the currently presumed knowledge (Tsuyoshi Takeda, Takagi, & Tsubakimoto, 2012). Meanwhile, the “traditional”, also named “conventional” start, was forgotten in favour of this two more recent alternatives, with exception for the changeovers, where it allows to the starting swimmer a better evaluation of the approach pathway of the colleague to changeover, as well as a better use of upper limbs momentum transfer without losing time during the inexistent reaction time phase. In this particular context of rules imposed constrains, swimmers began using “in movement” starts with the same intention of gaining momentum beforehand, but obviously restricted to the changeover starts.

A combination of the “traditional” and the grab start, was also proposed, trying to merge the advantage of both: the “one handed grab start”. Nevertheless, to the best of our knowledge, it was never used in major competitions, or, at least, with reasonable success. The same happened with the “tuck start”. However it was better received than the later. The availability of the new lateral hand supports (or the “old” Australian hand supports (also named as tuck start), may allow new explorations of this technique, where the swimmers positions such a way that his centre of mass falls ahead of the anterior edge of the starting block during the “take your marks” starting phase. So, this might be a technique for the future, but comparative kinetic data with other techniques are required once inexistent.

Indeed, the grab and track starts used in ventral events are the techniques most extensively studied (Vantorre et al., 2010a): in the first, the swimmers’ hands grasp the front edge of the block (either between, at the outer edge of the feet, or inclusively laterally) and in the later swimmers position one foot on the front edge of the starting block and the other behind, with the possibility of placing the body weight toward the front edge or at the rear of the block (Seifert et al., 2010; Vilas-Boas et al., 2003).

Some authors have studied the external forces that affect the swimmers’ movement on the starting block during the grab and/or track start techniques (R.

V. Breed & Young, 2003; Galbraith et al., 2008; Guimaraes & Hay, 1985; S. Slawson, Conway, P., Cossor, J., Chakravorti, N., West, A. , 2013; Vantorre et al., 2010b; Vilas-Boas et al., 2003) by measuring the total anterior-posterior (R. V. Breed & Young, 2003; Galbraith et al., 2008; Guimaraes & Hay, 1985; S. Slawson, Conway, P., Cossor, J., Chakravorti, N., West, A. , 2013; Vantorre et al., 2010b; Vilas-Boas et al., 2003), vertical (S. Slawson, Conway, P., Cossor, J., Chakravorti, N., West, A. , 2013; Vantorre et al., 2010b; Vilas-Boas et al., 2003) and lateral forces (Vantorre et al., 2010b). The vertical force application into the block accelerates the swimmer's centre of mass (CM) in the upward/downward direction, the anterior-posterior force generates propulsion mainly in the forward direction and the lateral force is essentially a heading movement control (Bäumker & Heimes, 2001; Lyttle & Benjanuvatra, 2005).

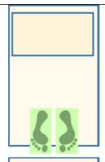
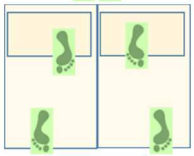
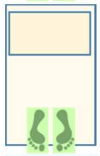
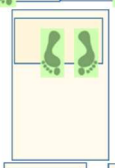
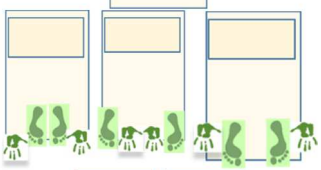
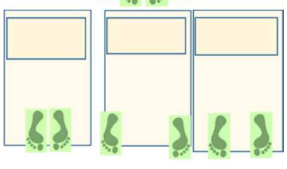
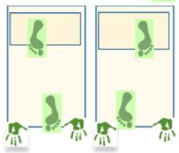
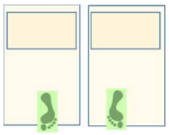
Therefore, the force time history in each contact limb is very important in the characterization of the propulsion in swimming start techniques (Mason et al., 2012). Force plates placed judiciously, can provide information of these measurements, and are called kinetic devices (Mason et al., 2012). The full characterization of the propulsion that describes the swimming start technique should include equipment for displacement body assessment that are called kinematic devices (Mason et al., 2012) which can be synchronized with the former instruments. The complete set of instruments allows the assessment of the 3D evolution of the contact force, centre of pressure (COP) and centre of mass (CM) displacement that can highlight the consequent flight features.

The more recent FINA's facilities rules (dated from 2009) imply narrow dimensional requirements for the block design which include: distance to water from top position; declination angle of top cap/cover of up to 10º; inclusion of an adjustable backplate for rear foot rest.

The main purpose of this work is to provide a tool to assess the GRF exerted on the swimmer while performing ventral starts characterized by actions of, mostly, all four limbs. Design should allow the evaluation and comparison of the different available and used techniques, and their variants, as well as guaranteeing compatibility solutions to backstroke start techniques assessment. It is urged a postural mapping for most start ventral techniques used by the swimmers.

The best way to map limb contact area is to imagine the regular block and list the main starts to be covered by the measuring device versus limb positioning. One important feature to be integrated on this reasoning is that no slippery is to be taken account of. So, contact is in the most cases with no relative limb contact to ground velocity. However centre of pressure of the body can move by changes of load from limb to limb or changing limb hand/foot to ground contact area. The following Table 2 resumes part of the check list to be observed.

*Table 2. Limb contact to block maps in various start techniques. Big rectangle represents the block itself while little rectangle represents backplate.*

| Initial position | Technique | End position |
|---|---|---|
|  | Conventional |  |
|  | One step |  |
|  | Two step |  |
|  | Grab |  |
|  | Track |  |

As each technique has its contact signature (or its sagittal symmetric, on account of laterality) it is possible to design a special layout (spatial layout) with a minimum of platforms. In order to build a load cell which can be reproduced to integrate on an instrumented starting block for full assessment of the GRF. At the same time a data acquisition system was defined, as well as its subsequent calibration procedures, record data strategies and data processing output in order to report delivery.

To map the universe of possible start techniques limb contact area, the Figure 11 depicts some of the contact to ground ventral possibilities as well as a relay change over example (grab start), where underwater platforms (which are object of another project) are synchronously included for data acquisition. This idea extends necessarily the concept of Table 2, as, for instance, there is no longer trigger event definition on relay changeover techniques. As there is no definition of load threshold to detect the underwater contact a different approach was performed. This way a shift register with a 6s window is used to record both signals after a centred trigger which is activated by a third subject or by the starting swimmer. Such event assessment is very subjective and therefore insidious but, in reality the trick is to maintain data acquisition in permanence discarding some early samples while acquiring fresh ones in a logic FIFO (first in first out shift registering). Looking at most events of research interest, it was evident that with a 6s window of centred trigger the necessary data acquisition would be covered.

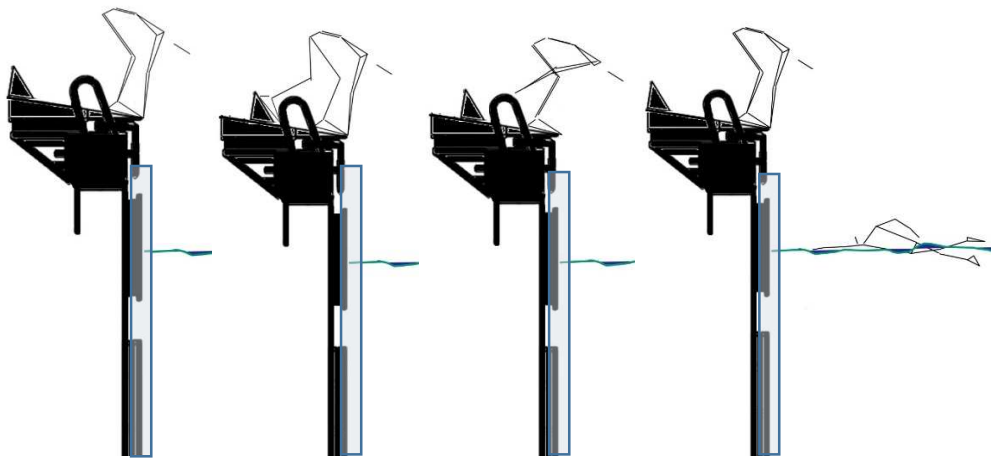


*Figure 11 map of all the possible limb contact to ground possibilities for platform number and insert positions definition as well as hardware for handgrips. The area in light grey represent objects of a complementary project.*

Bearing these maps in mind, the design of each of the platforms was subjected to the first constraints of insertion space, position available and dimension definition. In addition, and for economic reasons, it was interesting to replicate, if not all, at least part of the platforms set. After the definition of the dimensions of each platform, the load cell design was based on earlier results and in heuristics.

It was found that, with the experimented skills of the lab facilities, strain measurements using strain gauges would be the choice for the core of the load cell. However, Lywood geometry (Lywood, Adams, Van Eyken, & Macpherson, 1987; Roesler et al., 2006) has been chosen once, in this case, the load cell is an interpolation cell rather than an extrapolation device, in opposition to the one developed in Chapter 3.1. This has clear benefits in reducing force measurement uncertainty and also in position assessment of the Centre of Pressure (COP) (Bobbert & Schamhardt, 1990; L Mourão et al., 2015)

The setup requirements firstly included full compatibility with FINA's facilities rules (2009), as well as full 3D 6DoF (three dimensional, six degrees of freedom) limb contact force-moment measurement including some less common "tuck start" studies (with Australian and other hand grip solutions) and also the analysis of the influence of different block inclination angles as 0º, 5º, and 10º (FINA, 2009). These orientations were possible by using three metallic top covers which can be fixed on three inclined positions.

Other constraints to the design were: adequate topology or spatial positioning of the load cells, high speed multiple data acquisition, adequate mechanical shielding, mimicking the regular start block (by FINA's facilities rules, 2009) without compromising measurements and electrical security standards compliance following Figure 12 ("Portaria nº 949-A/2006 de 11 de Setembro. Regras Técnicas das Instalações Eléctricas de Baixa Tensão," 2006).

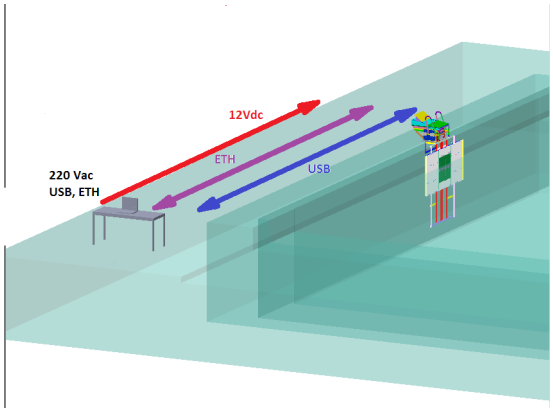



*Figure 12 Swimming pool possible device allocation suggested by RTIEBT 2006 compliance.*

To take the overall task forward it is still necessary to prove that a ‘metallic dress’, due to the use of the top covers, on the platforms does not compromise neither 3D force nor 3D momenta measurements. Such cover design would allow very different limb contact surface without high operation changes in the acquisition system. This way the assembly prototype will remain horizontal in all situations.

This demands a study of the algorithm to be applied for COP coordinates $(x, y, h)$ assessment. Usually, it is possible to determine the COP locus (or limb contact to ground locus Centre of Pressure, Figure 13) using the moment of force generated while in contact to platform. Moment of force is a vector quantity which is related to forces by the expressions:

$$\begin{cases} M_x = y \cdot F_z - h \cdot F_y \\ M_y = -x \cdot F_z + h \cdot F_x \\ M_z = x \cdot F_y - y \cdot F_x \end{cases} \qquad (6)$$

Where $\vec{r}_{COP} = (x, y, h)$ is the COP 3D position and respective coordinates, $x, y$ are centred with the platform cover centre, $h$ is the top cover depth to sensor loci, $\vec{F} = (F_x, F_y, F_z)$ is the force vector and respective coordinate components and $\vec{M} = (M_x, M_y, M_z)$ is the moment of the force and respective coordinate components. COP determination can be achieved by:

$$\begin{cases} x = \dfrac{h \cdot F_x - M_y}{F_z} \\ y = \dfrac{h \cdot F_y + M_x}{F_z} \end{cases} \qquad (7)$$

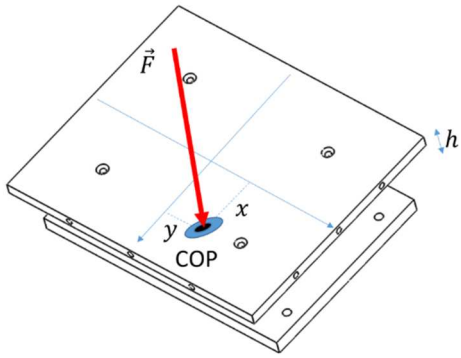



*Figure 13 Force and moment of force in decentred application point providing COP locus determination. 'x' is the distance from the higher axis to COP while 'y' is the distance to the smaller in this rectangular level platform.*

It is possible to determine the COP position, even if the platforms cover cap are not horizontal (Figure 14), providing the surface geometry or profile is known and planar, as it is the simplest profile description, as the following example definition of $h(x,y,a,b,c)$:

$$h(x,y)=a\cdot x+b\cdot y+c \tag{8}$$

Where a, b and c are constants provided by the planar platform cover cap geometry description. Where the top surface is inclined equations (6) change to:

$$\begin{cases} x=\dfrac{\begin{vmatrix}(M_x+c\cdot F_y) & (F_z-b\cdot F_y)\\ (M_y-c\cdot F_x) & (b\cdot F_x)\end{vmatrix}}{\Delta} \\ y=\dfrac{\begin{vmatrix}(-a\cdot F_y) & (M_x+c\cdot F_y)\\ (a\cdot F_x-F_z) & (M_y-c\cdot F_x)\end{vmatrix}}{\Delta} \end{cases} \tag{9}$$

With $\Delta=\begin{vmatrix}(-a\cdot F_y) & (F_z-b\cdot F_y)\\ (a\cdot F_x-F_z) & (b\cdot F_x)\end{vmatrix}$.

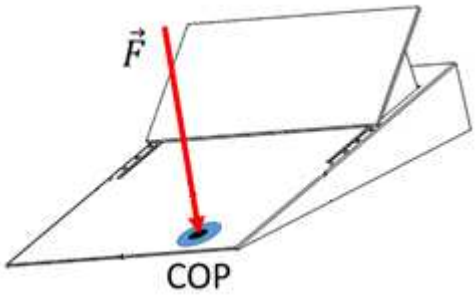



*Figure 14 Moment of force of decentred force providing COP locus determination in a planar cover non parallel to the plane of the platform.*

The following task of the development is, therefore, sequenced in the following steps:

1. The development of a preliminary prototype – in order to provide insight of the state of the art, a first prototype had to be tested;

2. Spatial and time layout option, limb positioning and signal double trigger;

3. Assembly configuration of the prototype– the adaptation of the first prototype to fulfil the various constraints;

4. Data acquisition system specs;

5. Static and dynamic calibration.

In this last step, the dynamic calibration presumes that the rigid body fall force-time curve is followed (Mourão *et al.*, 2015). This way the dynamic calibration can be performed avoiding the block disassemble. The prototype can be tested with platforms 'in situ' having in mind that the body release should be performed according to a given protocol. Such procedure saves time and can give hints on signal quality of the addressed channels.

## Materials and Methods

### *Preliminary prototype*

A preliminary platform using Lywood (1987) geometry was implemented for tests as depicted in Figure 15.

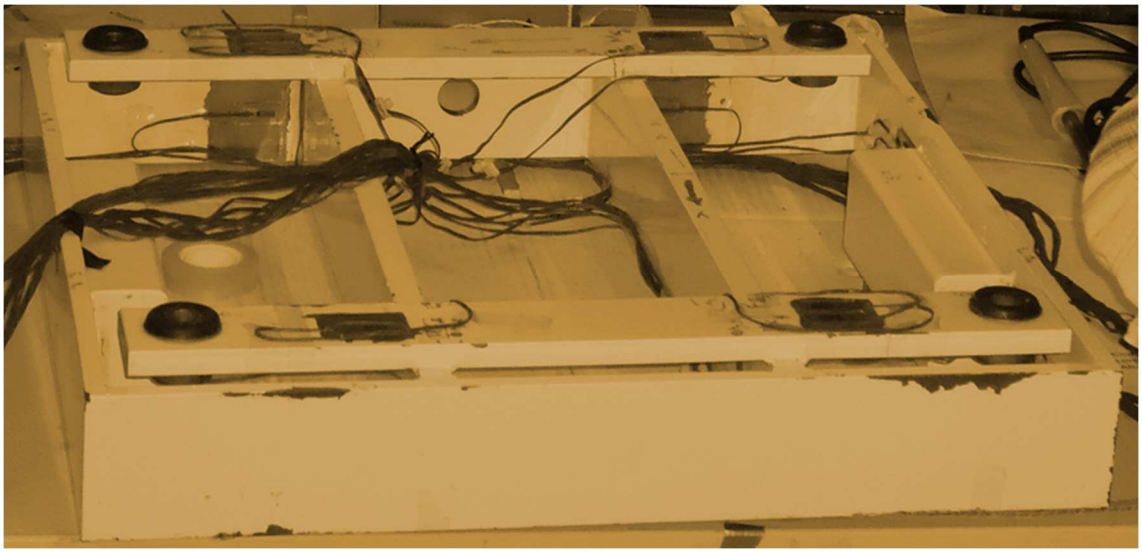


*Figure 15 Previous platform using Lywood geometry without cover/cap showing internal structure and strain gauge loci.*

This first prototype was designed based on the previous work and expertise of Roesler (Roesler, 1998), and aiming to serve as a testing tool for the ulterior development of the force plates. These are the sensors which are intending to integrate the final dynamometric device. The main requirements of the device (load sensor) were:

1) Instrumented bars oriented to be most sensitive to a given force or torque concerning component;
2) High distance between the centre cover anchorage points to obtain a better interpolation approach;
3) The platform was designed to remain immersed in the bottom of the swimming pool at 4m from the wall, this imposing the maximum cable length.

A full Wheatstone bridge (WB) configuration was selected for every of the 6 DoF instrumented component. To each of the WB a channel was attributed implying that a single platform requires six channels, which means: six independent power supplies and six strain signal output for each (*e.g.,* four wires per channel, two for excitation and two for signal data).

*Spatial and time layout*

The design of three dimensional force – six degrees of freedom (3D 6DoF) platforms provides simultaneous measurement of force $\vec{F}$, moment of force and Centre of Pressure position or $\overrightarrow{COP}$. It is important to realize that the COP is located in the contact region if a single limb is loaded, since, if not, it remains in between the contact limbs, masking postural constraints necessary for interpreting maximum performance data.

Such reasoning implies to individualize a limb-platform one-to-one relation of measurement. This shows the need to involve five platform to obtain a complete ventral device (spatial layout, Figure 16) because there are starting techniques requiring very different feet positioning, like the grab and the track starts (Table 2). Some notable features should be enhanced: blue area painted platforms belong to another PhD project but are to be included in order to evaluate relay changeovers, implying data acquisition accommodation; sagittal symmetry divides odd numbered from even numbered platforms.

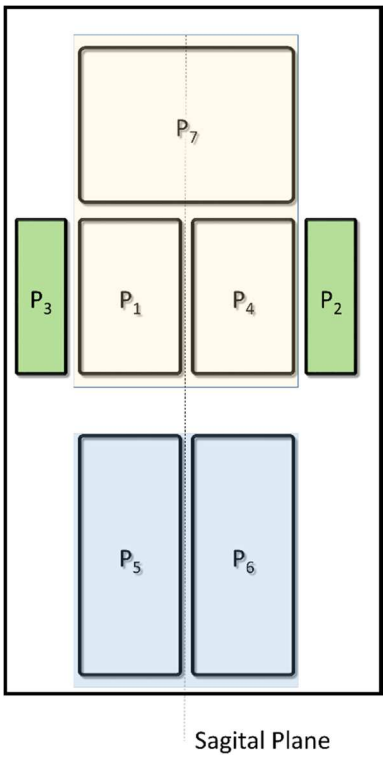



*Figure 16 platform in block distribution for individual limb 3D 6DoF force-moment assessment.*

Each of the limbs will contact to ground in one and only one of these platforms in the previous showed set. Such five platforms are unevenly distributed, as the rear lower limb always defines the laterality of the front limb. Such constraint, together with the possible laterality in grab start, indicate the need of two frontal platforms with a rear one that supports the adjustable backplate or footrest. This describes the spatial layout problem and its solution.

However, a more insidious problem arises: in relay changeovers there is no trigger signal, as the approach of the immersed swimmer triggers the changeover movement of the on block swimmer. No load threshold is defined because the separation between the swimmer contact load and the hydrodynamic forces is difficult and no capacitive sensors were available for this purpose. A third subject is required to centre more or less such event (without the need of more than reasonable accuracy). Therefore, it is necessary to particularize the assessment of the forces reacting to those applied by each limb (both hands and feet), turning the set of data necessarily stored in high dimension data arrays to accommodate of the various limbs time history and the contact to ground area variants, arising from choice or willingness (laterality differences) or taking account of the technique on study.

To cover the possible angles range, a transversal joint was designed to adjust the pitch angle. For the three top platform set was proposed the solution shown in Figure 17.

However, such knee design forecast some stability problems. Being the hand grips fixed the movement of the top platforms implies some complexity of the handgrips block anchorage. To maintain the distance between the backplate knee and the included handgrips an extensible mechanism had to be provided. Alternatively, the development of an algorithm to calculate COP, based on the math description of the contact surface declination, turned the fixed horizontal platform top adjustment with spare cover sets much more heuristic or attractive. The cover sets provide the declination of 5 and 10º (being the last as FINA's facilities rules state as the higher limit). Included, in both sets, an adjustable backplate, to complete the FINA's facilities rules statements, allowing the use of

the block, although instrumented, as a regular block. This is another target: to provide the mimethism to the standard block so that swimmers would notice an ecological and regular competition device.

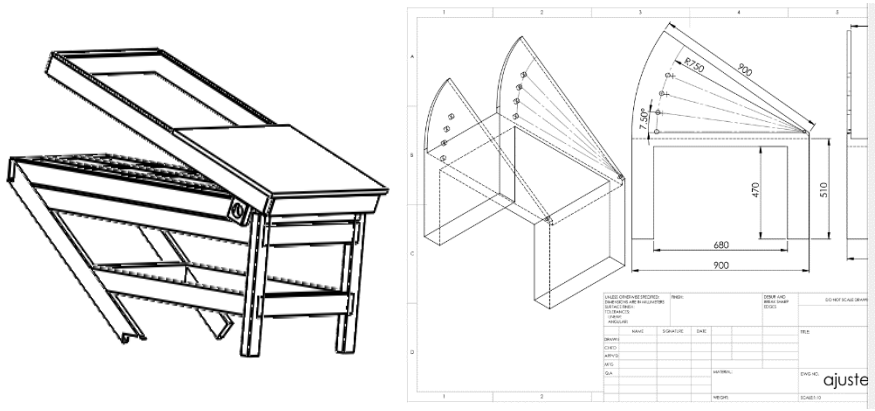



*Figure 17 Adjustable angle declination for the top set of three platforms.*

*Final prototype*

The available on block spatial platform distribution imposed dimensional constraints by the following reasons:

1) Project required FINA facilities rules comply
2) Material choice imposed most of the weight, volume and other features either to block structure either to platforms themselves, as well to the choice of the strain gauge to comply simultaneously water resistance (or, even worse, taking account of chloride present in swimming pool). This way steel was the most adequate choice for the application.

Particularly in the second topic it was made a numerical simulation of the total strain for the handgrips and for the structure of the platforms with ANSYS 14.0 software (ANSYS® Workbench™ 2.0 Dassault Systems, France). The results are depicted in Figure 18. It can be seen that the value is high as is the distance of the force applied to the platform. It is hoped to have same strain with a double force but half distance to anchorage (the lateral platform cap cover).

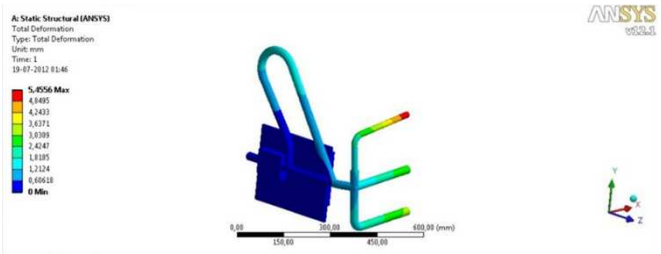



*Figure 18 Numerical simulation of the strain produced in the handgrips for 600N load.*

For comparison of platforms behaviour it was desirable to have subsets of similar platforms. So, platforms 1, 2, 3 and 4 are similar as well as 5 and 6, this way providing interchangeability, which might be of great importance if mass production or maintenance are considered.

After the task of mechanic hardware implementation has taken place, strain gauges were bonded to the platforms. Every platform obeys the same structural and implementation concept (Lywood 1987) and, therefore, a unique example of strain gauge bond layout platform follows. The platforms, though, are designed with different dimensions, depending on the anchorage locus, docking specs, forces ranging up to 4000 N and higher than 2000 Hz resonance frequency. For material homogeneity purposes, as lab facilities tools for component implementation would be the same, it has been decided to implement the platforms made by steel. As underwater use is at sight or, at least, intense moisture is expected in the swimming pool environment, the strain gage choice was KFW-5-120-C1-5M2B (Kyowa, Electronic Instruments, Japan).

Although some of the strain gage are in similar places of others, Wheatstone bridge connection disambiguate their mechanical sensor function. In Figure 19 is depicted the complete strain gauge bonding and respective Wheatstone bridge topology and connection (power and signal cables are considered exiting to the right of the structure, defining x (platform self-frame also defines z direction positive as cap cover plane above oriented, while y ) positive direction, sensor measures the force applied, or, its negative is the GRF positive sense; coloured orange strain gauges remain in hidden faces while blue are at sight).

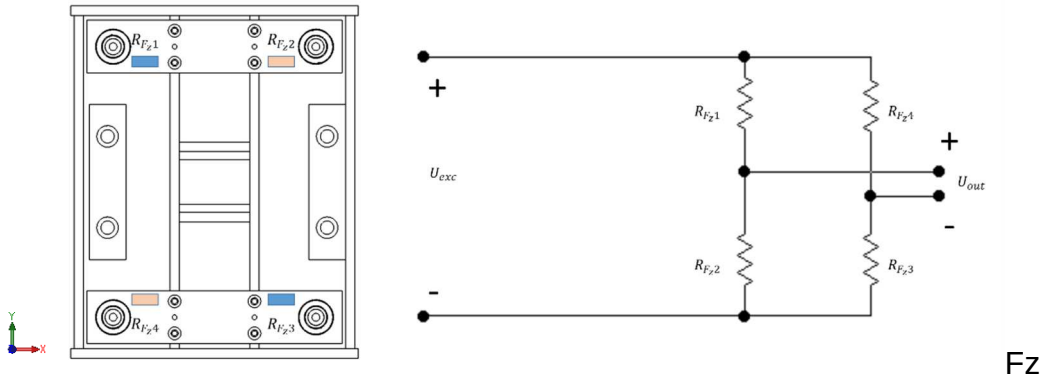
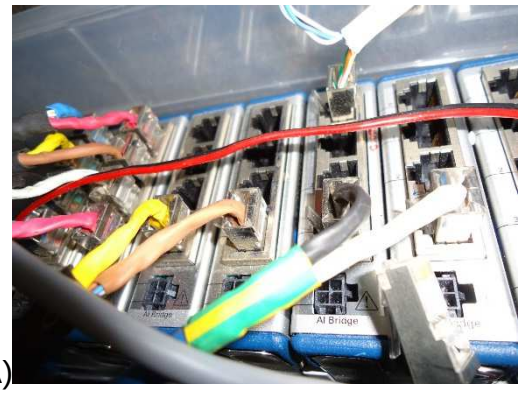



*Figure 19 Exemplar strain gauge loci and respective connection diagram. Orange means the invisible face location while blue represents the visible side. At the middle the corresponding diagram of the Wheatstone bridge, and at the right panel, the identification of the component to be measured with.*

The strain gauges were identified by digit codes and in Figure 20, it can be seen that cable wiring has also been standardized with colour code jacket terminals nearby the RJ50 plug (plugged in the Ni 9237). Cable plugs are bundled always with the same pair of components.

A) 

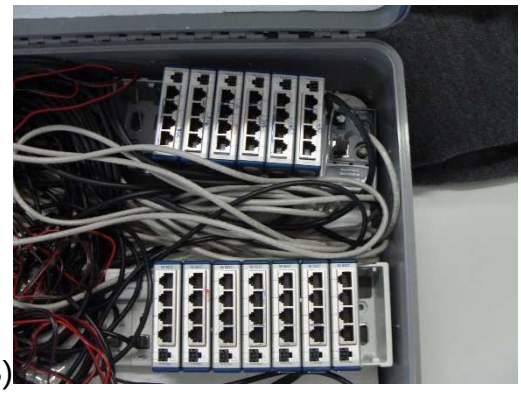
B) 

*Figure 20 Two chassis view of the final connection to data acquisition system: a) cable color codes provide connection identification of Wheatstone bridge; b) the complete set of modules in respective chassis in a future moisture insulation case.*

The wired numbered strain gauges are in the loci defined by schemes similar to the represented in Figure 19. So, welding board is provided to implement physically the Wheatstone bridges. However, pool moisture (and the presence of chloride ion) is a strong oxidant to welding points. The strategy was, therefore, to insulate the board with the suitable injected on mold silicon envelopes whose

suitable geometry allows stowage inside the free inner space provided by the platform structure.

A subcontract service in order (Figure 21 A panel) to ensure the hardware quality of the metallic components used in the platform implementation and the assembly maintenance follow-up of the strain gauge during the tests. Also, in case of maintenance, a water insulation material is provided to protect WB welding points.

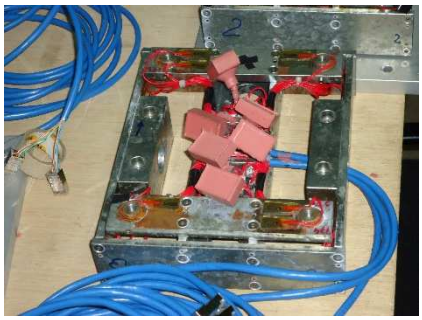
A)  B)  C)

*Figure 21 A) Maintenance of platforms B) water insulation of the welding points of each Wheatstone bridge at service facilities.*

Figure 22 depicts one of the platforms implemented in standalone mode.

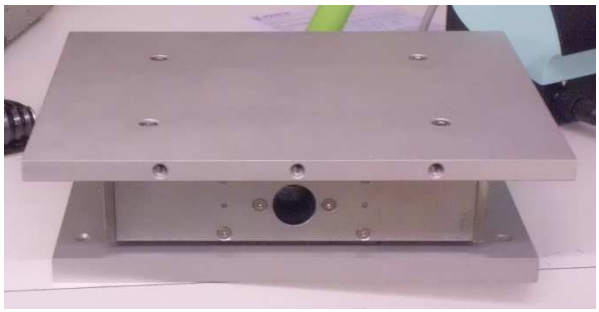


*Figure 22 Assembled platform standing alone. Note the screw holes in the top cover lateral face for calibration procedures use.*

With the example above all the platforms were reproduced similarly.

## Data acquisition system

The Spatial and time layout problems led to design of the data acquisition system compatible with such requirements. Figure 23 represents the main flow data diagram of the data acquisition system.

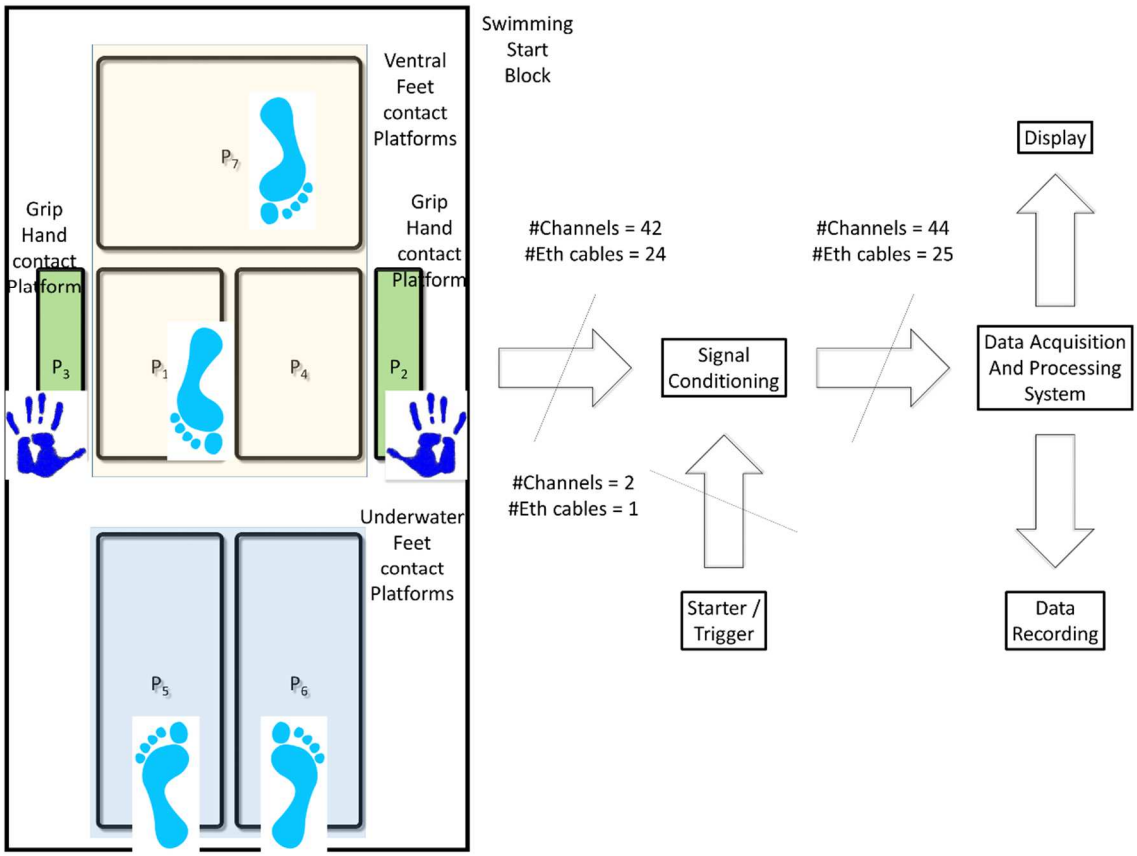



*Figure 23 The complete data acquisition system: the system start block connects to signal conditioning and to data acquisition and processing system for data recording or observation.*

As observed in Figure 20 B panel, there is a lot of data input to data record, so the main task is to guarantee data record. Data conditioning is connecting in the same block two different chassis with the same NI9237 modules. Indeed there are differences between chassis (NI9188 Ethernet connection and NI9172 USB 2.0 connection). With interpreted LabVIEW® (National Instruments Corporation, USA) the synchronism was obtained increasing the time window from 6 to 8s (adapted already for relay changeovers) and acquire not one but two channels in each chassis for the trigger signal.

The data system specs include, therefore, high channel number (42 channels + 2 trigger channels) at high sample rate (2 ksample/s), two scanner chassis from National Instruments, NI 9172 and NI 9188 supporting seven and six 4-channel National Instruments NI 9237 4xChannel half/full bridge 24 bit DAC modules, respectively.

Our choice was a heuristic solution, as there were free channels in each of the chassis. The Figure 24 depicts the solution applied.

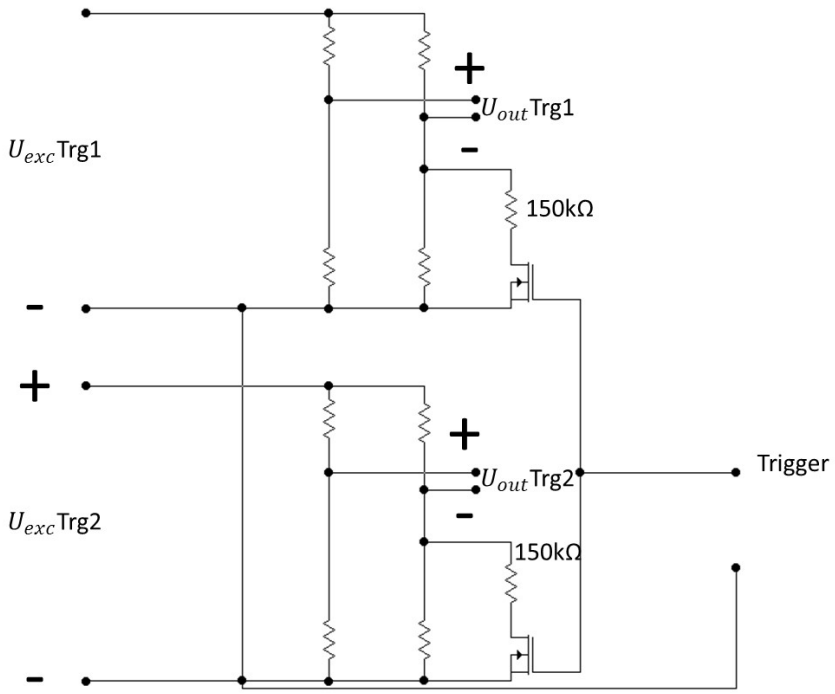



*Figure 24 Trigger schematic design for clock through phase information in the data acquisition system.Trg1 and Trg2 should be connected to free channels in each 9172 and 9188 chassis.*

As can be seen, these are two twinned mute Wheatstone bridges that are mimicking an almost regular strain gauge Wheatstone bridge. This allows the two extra above mentioned channels to be included in the array of addressed channels without any other change to the hardware than inclusion of two more channels, one per chassis. In post-processing, it is possible to adjust and synchronize all the channel signals.

Software, however, had to be rearranged particularly at the sight of the shift register data maintaining the last four seconds in memory. The emulation of circular memory of 4s with 1s division, meaning that the last acquired 1s of data will substitute the previous 1s and the previous 1s the earlier 1s, and so on until the earliest which will be discarded. This prefigures a characteristic circular memory of 4s FIFO (1s division) If a trigger signal appears routine behaviour changes and 4s of more data are concatenated being saved immediately after 4s trigger fired.

### Calibration and complete setup

Calibration procedures, were implemented with calibrated masses of 10kg and in static positioning. Figure 25 represents centred force z component calibration (A panel) and y component calibration (B panel). There was a set of 5 lead weights of ~10kg each that, sequentially, loaded the platforms in each positioning. 5 places were used in the top cap cover and three lateral positioning.

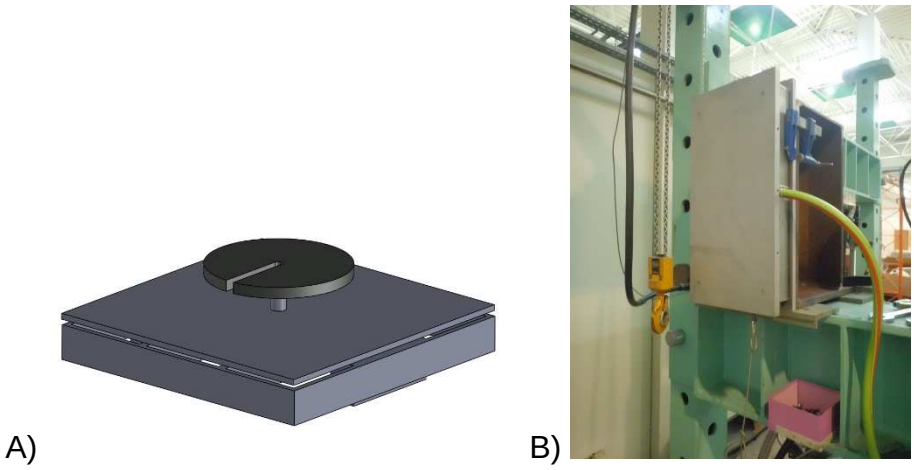



*Figure 25 A) The setup was reproduced for 10 kg mass stack of up to ~1100 N. B) Setup for lifting up to 1100 N in tangential direction for calibration of the tangential forces. The use of a strong anchorage was necessary.*

Dynamical responsiveness, following Chapter IV (L Mourão et al., 2015) of this thesis, means that it is possible to apply a variable load in time but with values that are modelled by some physical theoretical model that remains unchanged (good repeatability) and so it is possible to implement dynamical calibration

providing there is a known inertial moment of a free falling rigid object. If this is the case, calibration can be effective even with platforms mounted.

For dynamical observation, a rigid body with known Inertia tensor is used as Figure 26 depicts. This rigid body can be used for free fall observation and measurement. Such curves can be integrated in a quick calibration procedure.

*Figure 26 Rigid body centre of mass position determination.*

In the development of the routine to acquire data, special attention has been paid to data history control. A total 8 seconds data history, [-4s,+4s] around trigger input, is saved in the acquisition files, rising to 8 Megabyte of data. This is achieved with an algorithmic structure of a cycle with ‘shift register’ that, until 4 seconds operates ‘append waveforms’ and thereafter discards the first 2000 samples appending the brand new 2000 samples of the following data acquisition to the queue of data. This process remains until the trigger is activated. At that instant more 8000 samples are added to the earlier data stored and are saved in data file with a serial number concatenated to the name given by the user to prevent loss of information. Data is saved in strain units for later processing. However, as pool water is a very harsh media for strain gauge integrity, turning its signals erratic and noisy or even to study part of the channels available, individual channel enabling and disabling data channels presentation control is possible, selecting in the virtual ‘led’ selection array which are to be on/off. Figure 27 presents the acquisition data routine front end.

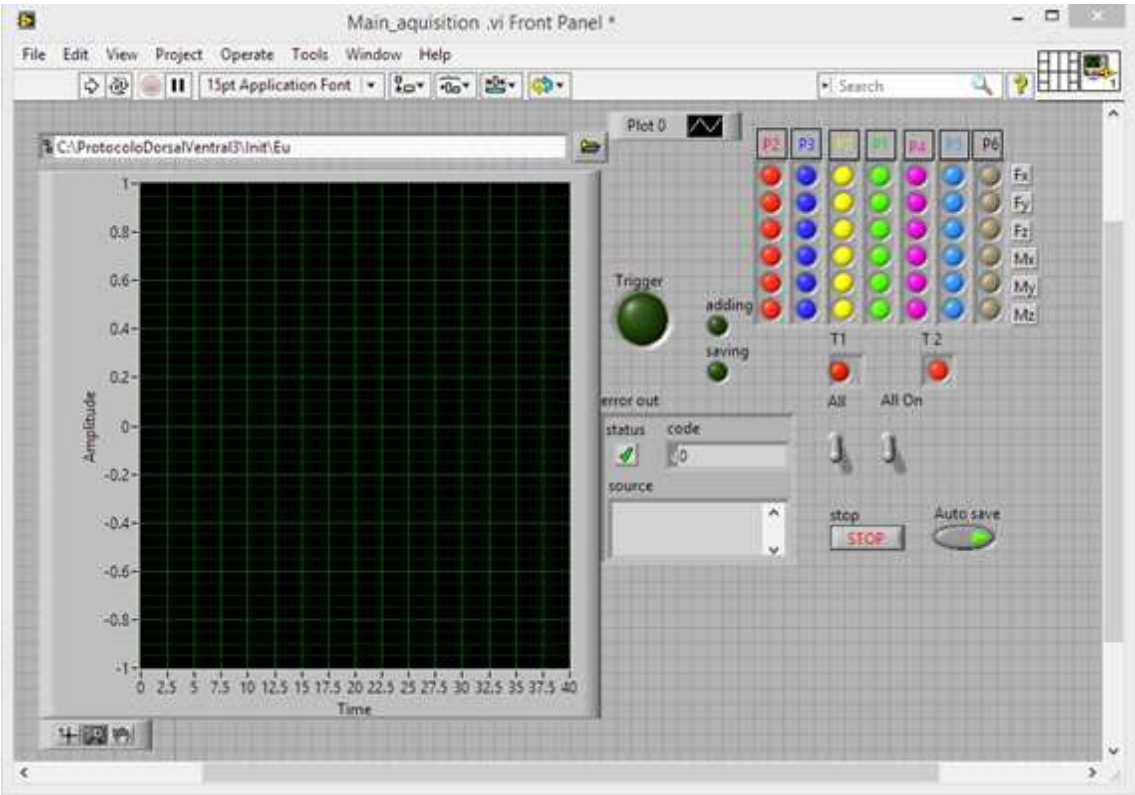



*Figure 27 The acquisition data routine front panel. Coloured vertical 'led' arrays are selection channel data visualization for the respective platforms.*

The data acquisition files can be later operated to transform strain signals in force-moment with the aid of (presently) matlab (Mathworks inc, USA) routines for the required matricial operations of conversion. They apply conversion based on the linear fit (in a first approximation as in Figure 28 ) or, if necessary, and there is a strong hint that there is a non-linear dependency there are non-linear re-calibration algorithms (Cappello et al., 2011) or with some crosstalk present, a matricial algorithm is applied in order to obtain the conversion signal to force-moment matrices.

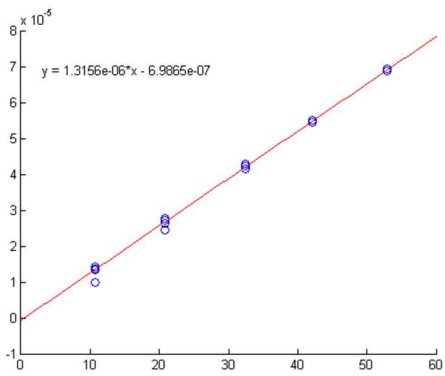



*Figure 28 Exemplar calibration curve of $F_z$ with increments of 10 kg.*

Calibration results are collected and curve fitting based on linear fitting (polinomials of degree 2 usually are not needed) lead to the transfer function. In general there is a small and negligible ($\sim 1\%$) crosstalk between orthogonal sensors. Otherwise, higher responsiveness could imply the use of non-diagonal transfer function matrix. It has not been our main experience. Usually, the least responsive channels, generating higher crosstalk on account of the lack of sensitivity, are also short mean life, implying sensor maintenance (substitution). Nevertheless, there is an aprioristic higher 'z' axis sensitivity for forces than 'x' or 'y'. Also, there might be a delay of about 1/1500 s between sensors $F_z, M_x, M_y$ and $F_y$ and $F_x, M_z$. This is the result of force propagation through solid media path which is different from force/moment component sensor.

Some exemplar mean conversion factors are showed (in platform frame coordinates)

| Channel | Conversion factor |
|---|---|
| ATrgEth | 1E5 |
| AFxP2 | 1849184.924 |
| AFyP2 | -750491.2843 |
| AFzP2 | 20546486.37 |

The complete setup looks like the following Figure 29, A and B panels.

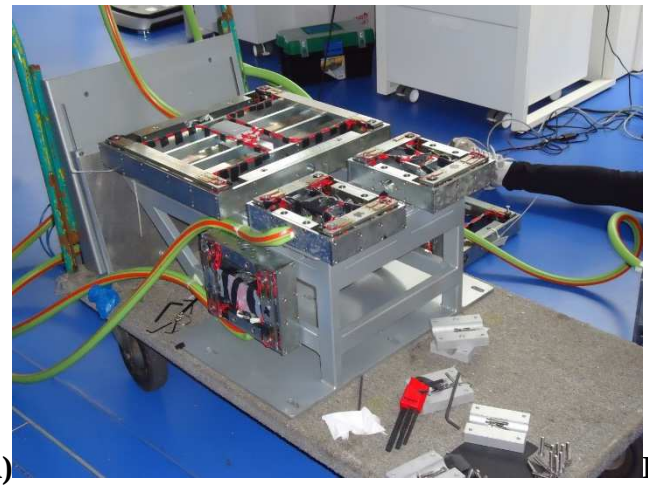
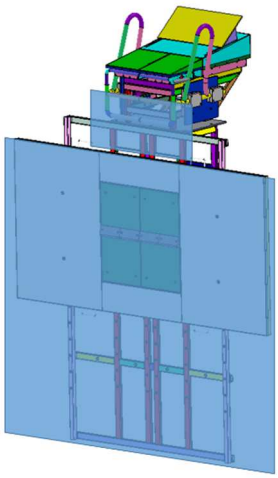
A)  B) 

*Figure 29 A) Platforms installation on respective block positions anchorage. B) The complete hardware solution for the block setup. Shaded areas belong to other PhD project.*

Although calibration procedures are (by construction) inherited from platform to platform, conversion to ISB standard is necessary to standardize the transfer function of each platform. The reasoning is depicted in the Figure 30.

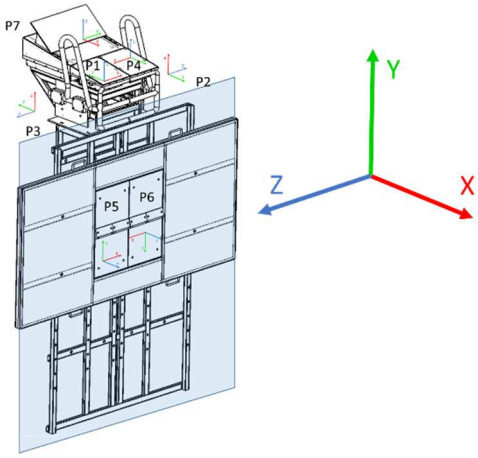



*Figure 30 Frame ISB (large) and inner frames of each of the platforms in a common configuration. Platforms P1, P2, P3 and P4 and interchangeable as are P5 with P6. Cables are always placed laterally out or down except that of P7 which are rear placed.*

Bearing this configuration in mind, it is possible to convert all data to ISB framework by applying the following matrices to the vectors Force and Moment of force generated by each of the platforms:

P1: $A_{P1ISB} = \begin{bmatrix} +0 & -1 & +0 \\ +0 & +0 & +1 \\ -1 & +0 & +0 \end{bmatrix}$; P2: $A_{P2ISB} = \begin{bmatrix} +0 & +1 & +0 \\ +1 & +0 & +0 \\ +0 & +0 & -1 \end{bmatrix}$;

P3: $A_{P3ISB} = \begin{bmatrix} +0 & -1 & +0 \\ +1 & +0 & +0 \\ +0 & +0 & +1 \end{bmatrix}$; P4: $A_{P4ISB} = \begin{bmatrix} +0 & +1 & +0 \\ +0 & +0 & +1 \\ +1 & +0 & +0 \end{bmatrix}$;

P5: $A_{P5ISB} = \begin{bmatrix} +0 & +0 & +1 \\ +0 & +1 & +0 \\ -1 & +0 & +0 \end{bmatrix}$; P6: $A_{P6ISB} = \begin{bmatrix} +0 & +0 & +1 \\ +0 & -1 & +0 \\ +1 & +0 & +0 \end{bmatrix}$;

P7: $A_{P1ISB} = \begin{bmatrix} +1 & +0 & +0 \\ +0 & +0 & +1 \\ +0 & -1 & +0 \end{bmatrix}$

As can be seen, and by construction, once again, platforms P1 to P4 (250x300) are interchangeable, meaning that these matricial operations might be applied in the respective new position matrix conversions by simple interchange matrices, after individual transfer matrix application. This is an attractive topic, as maintenance operations can turn inoperative some of the platforms during data collection and this property might mitigate for part of the work carriage.

The complete setup when installed at the swimming pool should look as is depicted in Figure 31.

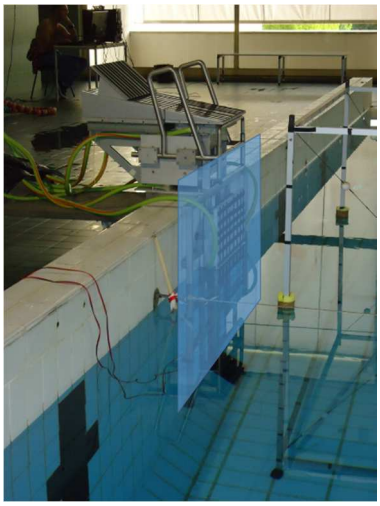


*Figure 31 Complete setup installation and ready to use.*

At this time the overall operation time spent can be in the order of minutes, but future efforts for optimization should be applied in the inclusion of these steps to the main acquisition LabVIEW routine for one sole interface without sub-steps or extra-step routines, and less than a minute of feedback to the swimmer.

Despite the essential contribution of the previous research regarding the external kinetics involved at ventral swimming starts, the process of interpreting and analysing data is still not as effective as it should (S. Slawson, Conway, P., Cossor, J., Chakravorti, N., West, A. , 2013). Based on fundamental mechanics,

the forces applied on the starting block should be interpreted as dependent on active and the body weight dynamical effects in each successive body position. Using Newton's 3rd law, the total reaction force exerted by the starting block on the swimmer ($\overrightarrow{GRF}(\mathrm{t})$) is the opposite of the action force applied on the block surface, and it contains swimmer's muscular action and postural effect while moving (changing multi-body configuration and CM position).

It will be possible, in the future to include a routine to split active from passive forces in real time for coach aid. Also, although it had been possible to prove the concept in chapter 3.1, there is not, yet, a routine for force and centre of pressure graphical 3D presentation for individual limb or 5x(3D 6DoF) force-COP graphical interface. Extending the concept to accommodate the underwater platforms, the system would be 7x(3D 6DoF).

**Conclusion**

A new topology was used to load cells implementation reducing some of the issues of the previous load cell development.

A complete setup was implemented obeying the implementation rules provided in the text. These included the choice of the complete set of platforms and the core reproduction for each location position.

Metallic hardware for pool anchorage and for declination angle materialization was implemented. The choices for angle materialization were led by math model of the surface and its impact on the moment of force, while articulated declination offered more possible flexibility but much less anchorage and stiffness. The same concept allows determination of position of the hands determination.

The topology used by the Wheatstone bridge was also the suggestion for the trigger implementation allowing its insertion without any more electronic hardware and simplifying the software, without any loss of general purpose use.

However, post processing indeed remains necessary. Next step might be the integration of all modules developed as the new routine proved to get closed to synchronism without this resource.

Calibration was effectively applied with static force exerted by masses. However a quick possibility is to apply the free fall of a rigid body whose curve is already well known as can be seen in chapter 4.

The excessive amount of channels imply that a huge effort has to be invested in selection capabilities. Some of the issues that are to be considered appear on account of the inclusion of the underwater platforms on the overall device. Such inclusion implies the use of a second chassis, introducing a possible non synchronism in real time observation, causing possible miss-validation of recent observed data. So, forecasting the rise of difficulties in data interpretation, it is important to have a selection tool at hand and in the future the development of automatic failure detection.

As a conclusion, it is possible to measure the individual limb to ground force generation and posture loci in swimming start techniques. In the chapter 4 it will be shown added capabilities to split active from passive force. The tool should be very complete and should be a good aid for coaching activities.

**Conflict of interest statement**

The authors declare that they have no conflict of interest but this communication is not publishable.

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## References


Bäumker, M., & Heimes, F. (2001). *New calibration and computing method for direct georeferencing of image and scanner data using the position and angular data of an hybrid inertial navigation system.* Paper presented at the OEEPE Workshop, Integrated Sensor Orientation.

Bobbert, M. F., & Schamhardt, H. C. (1990). Accuracy of determining the point of force application with piezoelectric force plates. *Journal of Biomechanics, 23*(7), 705-710.

Breed, R. V., & Young, W. B. (2003). The effect of a resistance training programme on the grab, track and swing starts in swimming. *Journal of Sports Sciences, 21*(3), 213-220.

Cappello, A., Bagalà, F., Cedraro, A., & Chiari, L. (2011). Non-linear re-calibration of force platforms. *Gait & Posture, 33*(4), 724-726.

FINA. (2009). Fedération Internationale de Natation. Facilities Rules. http://www.fina.org Retrieved 12 September, 2014

Galbraith, H., Scurr, J., Hencken, C., Wood, L., & Graham-Smith, P. (2008). Biomechanical comparison of the track start and the modified one-handed track start in competitive swimming: An intervention study. *Journal of applied biomechanics, 24*(4), 307-315.

Guimaraes, A. C. S., & Hay, J. G. (1985). A mechanical analysis of the grab starting technique in swimming. *International Journal of sport biomechanics, 1*(1), 25-35.

Lyttle, A., & Benjanuvatra, N. (2005). Start Right–A Biomechanical Review of Dive Start Performance. *Zugriff am, 15*.

Lywood, D., Adams, D., Van Eyken, A., & Macpherson, J. (1987). Small, triaxial force plate. *Medical and Biological Engineering and Computing, 25*(6), 698-701.

Mason, B., Mackintosh, C., & Pease, D. (2012). *The development of an analysis system to assist in the correction of inefficiencies in starts and turns for elite competitive swimming.* Paper presented at the ISBS-Conference Proceedings Archive, Melbourne: Australian Catholic University.

Mourão, L., de Jesus, K., Viriato, N., Vilas-Boas, J. P., Monteiro, J., & Vaz, M. A. P. (2015). Design and construction of a 3D force plate prototype for developing an instrumented swimming start block. *Submitted to Journal of Biomedical Engineering and Informatics*.

Portaria nº 949-A/2006 de 11 de Setembro. Regras Técnicas das Instalações Eléctricas de Baixa Tensão. (2006).

Roesler, H., Haupenthal, A., Schütz, G. R., & de Souza, P. V. (2006). Dynamometric analysis of the maximum force applied in aquatic human gait at 1.3 m of immersion. *Gait & Posture, 24*(4), 412-417.

Seifert, L., Vantorre, J., Chollet, D., Toussaint, H. M., & Vilas-Boas, J.-P. (2010). Different profiles of the aerial start phase in front crawl. *The Journal of Strength & Conditioning Research, 24*(2), 507-516.

Slawson, S., Conway, P., Cossor, J., Chakravorti, N., West, A. . (2013). The categorisation of swimming start performance with reference to force generation on the main block and footrest components of the Omega OSB11 start blocks. *Journal of Sports Sciences, 31*, 468 - 478.

Takeda, T., Takagi, H., & Tsubakimoto, S. (2012). Effect of inclination and position of new swimming starting block's back plate on track-start performance. *Sports Biomechanics, 11*(3), 370-381.

Vantorre, J., Seifert, L., Fernandes, R., Vilas-Boas, J., & Chollet, D. (2010a). Kinematical profiling of the front crawl start. *International journal of sports medicine, 31*(01), 16-21.

Vantorre, J., Seifert, L., Fernandes, R., Vilas Boas, J., & Chollet, D. (2010b). Comparison of grab start between elite and trained swimmers. *International journal of sports medicine, 31*(12), 887-893.

Vilas-Boas, J. P., Cruz, J., Sousa, F., Conceicao, F., Fernandes, R., & Carvalho, J. (2003). *Biomechanical analysis of ventral swimming starts: Comparison of the grab start with two track-start techniques.* Paper presented at the Biomechanics and Medicine in Swimming IX, Saint-Étienne, France.

# Chapter 4

## Effective swimmer's action during the grab start technique

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## Abstract

The external forces applied in swimming starts have been often studied, but using direct analysis and simple interpretation data processes. This study aimed to develop a tool for vertical and horizontal force assessment based on the swimmers' propulsive and structural forces (passive forces due to dead weight) applied during the block phase. Four methodological pathways were followed: the experimented fall of a rigid body, the swimmers' inertia effect, the development of a mathematical model to describe the outcome of the rigid body fall and its generalization to include the effects of the inertia, and the experimental swimmers' starting protocol analysed with the inclusion of the developed mathematical tool. The first three methodological steps resulted in the description and computation of the passive force components. At the fourth step, six well-trained swimmers performed three 15 m maximal grab start trials and three-dimensional (3D) kinetic data were obtained using a six degrees of freedom force plate. The passive force contribution to the start performance obtained from the model was subtracted from the experimental force due to the swimmers resulting in the swimmers' active forces. As expected, the swimmers' vertical and horizontal active forces accounted for the maximum variability contribution of the experimental forces. It was found that the active force profile for the vertical and horizontal components resembled one another. These findings should be considered in clarifying the active swimmers' force variability and the respective geometrical profile as indicators to redefine steering strategies.

*Keywords*: biomechanics, dynamometry, modelling, swimming, ventral start

## Introduction

It is known that the 15 m starting performance can differ amongst elite swimmers by only ~0.40 s (Mason et al., 2012; Seifert et al., 2010), with a decisive effect on the final result in several competitive events. The grab and track starts used in ventral events are the most extensively studied techniques (Vantorre et al., 2010a): in the grab start, the swimmers' hands grasp the front edge of the block

(either between or at the outer edge of the feet) and in the track start swimmers position one foot on the front edge of the starting block and the other foot behind, with the possibility of placing the body weight toward the front edge or toward the rear of the block (Seifert et al., 2010; Vilas-Boas et al., 2003).

Some authors have studied the external forces that affect the swimmers' movement on the starting block during the grab and/or track start techniques (R. V. Breed & Young, 2003; Galbraith et al., 2008; Guimaraes & Hay, 1985; S. Slawson, Conway, P., Cossor, J., Chakravorti, N., West, A. , 2013; Vantorre et al., 2010b; Vilas-Boas et al., 2003) by measuring the total anterior-posterior (R. V. Breed & Young, 2003; Galbraith et al., 2008; Guimaraes & Hay, 1985; S. Slawson, Conway, P., Cossor, J., Chakravorti, N., West, A. , 2013; Vantorre et al., 2010b; Vilas-Boas et al., 2003), vertical (S. Slawson, Conway, P., Cossor, J., Chakravorti, N., West, A. , 2013; Vantorre et al., 2010b; Vilas-Boas et al., 2003) and lateral reaction forces (Vantorre et al., 2010b). The vertical force applied into the block accelerates the swimmer's centre of mass (CM) in the upward/downward direction, the anterior-posterior force generates propulsion mainly in the forward direction and the lateral force is essentially a controlling movement (Lyttle & Benjanuvatra, 2005).

Despite the essential contribution of previous research regarding the external kinetics involved during ventral swimming starts, the process of interpreting and analysing data is still not as effective as it should be (S. Slawson, Conway, P., Cossor, J., Chakravorti, N., West, A. , 2013). Based on fundamental mechanics, the forces applied on the starting block may be interpreted as being dependent upon the active forces and the body weight dynamical effects in each successive body position enabling to provide more accurate information about performance diagnosis (Holfelder, Brown, & Bubeck, 2013). Using Newton's 3rd law, the total ground reaction force exerted by the starting block on the swimmer $\left(\overrightarrow{GRF}(t) = \left(GRF_h(t), GRF_v(t)\right)\right)$, where it has been separated into its most relevant components accordingly to (Lyttle & Benjanuvatra, 2005), is the opposite of the action force applied on the block surface, and it involves the swimmer's muscular action and postural effect while moving (changing multi-segment configuration and CM position). Sometimes the vertical component of GRF is termed $\overrightarrow{N}$, the

normal reaction, and the horizontal component is termed $\vec{F}_s$, the static friction. Returning to the swimming start block, the swimmer's acceleration is defined through Newton's 2nd law as:

$$\overrightarrow{GRF}(\mathrm{t}) + \vec{W} = \mathrm{m} \cdot \vec{a}_{\mathrm{swimmer}}(\mathrm{t}) \qquad (10)$$

Where $\vec{W}$, $m$ and $\vec{a}_{swimmer}(t)$ are the swimmer's weight, mass and acceleration, respectively, being $\overrightarrow{GRF}$ applied at the halluces (feet) and $\vec{W}$ at the centre of mass. In accordance, the total impulse or linear momentum increment $(\Delta\vec{p})$, leading to CM kinematics classical description is defined as the time integral:

$$\int_0^{\tau} \left( \overrightarrow{GRF}(\mathrm{t}) + \vec{W} \right) \cdot \mathrm{dt} = \Delta\vec{\mathrm{p}} \qquad (11)$$

However, even in the absence of a swimmer's active starting effort, impulse generation remains, which can be evidenced by considering the fall of a similar passive rigid body. Therefore, in this particular case, the $\overrightarrow{GRF}(t)$ is simply a passive force, that is:

$$\overrightarrow{GRF}(t) = \vec{R}_{Passive}(t) \qquad (12)$$

The $\vec{R}_{Passive}(t)$ (the $\overrightarrow{GRF}(t)$ applied to the inertial structure of the swimmer's body) should be considered in this formalism as the one generated by a falling inert rigid body. Keeping in mind these ideas, it is suggested to decompose $\overrightarrow{GRF}(t)$ in the general (and real) case into passive and active components, as:

$$\overrightarrow{GRF}(t) = \vec{R}_{Passive}(t) + \vec{R}_{Active}(t) \quad (13)$$

where $\vec{R}_{Active}(t)$ is in the opposite direction to that of the propulsive force vector applied to the block by the swimmer's muscular actions and $\vec{R}_{Passive}(t)$ is the same as in Equation 12.

The aim of this research is to decompose the $\overrightarrow{GRF}(t)$ into $\vec{R}_{Active}(t)$ and $\vec{R}_{Passive}(t)$ in the grab start, which is one of the most used ventral starting techniques (Seifert *et al.* 2010, Vantorre *et al.* 2010, Vantorre *et al.* 2010b, Elipot *et al.* 2009). This start technique is the most suitable to apply the force splitting formalism, since the swimmer's body is in contact with the platform by means of the halluces-platform alignment whose centre should be the centre of pressure (COP). In fact, this particular geometry may be described as the CM rotation around the halluces lateral-medial axis, combined with the CM displacement along the anterior-posterior CM-COP direction. As this geometry is partly shared with the track start, a similar approach can be applied when the swimmer's rear lower limb leaves the block. It is hypothesised that it is possible to decompose $\overrightarrow{GRF}(t)$ into its $\vec{R}_{Passive}(t)$ and $\vec{R}_{Active}(t)$ components, allowing researchers and coaches to better understand the real swimmer's force generation contribution during the block phase.

## Material and Methods

### General description

Four working pathways were followed: (i) the experimented fall of a simple rigid body; (ii) the swimmers' matrix of inertia determination; (iii) the development of a mathematical model to describe the outcomes of the rigid body fall experiment and its generalization to provide replacement of the calculated inertia; and (iv) the experimental start protocol and data analysis including the developed mathematical model. The first three steps were defined to achieve the transient swimmer's angular positions during the starting movement in order to better understand the influence of the passive forces on start performance.

## Physical rigid body falling

A rigid rectangular stainless steel structure ($1.80m$ in height, $0.30m$ in width and $27kg$ total mass) was used. The structure CM was located at $0.90m$ height and two stainless steel masses ($10kg$ each) were fixed at that height in each structure side. The lower extremity structure's was rectangular and divided into two contact surfaces ($0.044m \times 0.037m$) (Figure 32A). To simulate the support of the swimmer's feet, the structure was balanced at the front edge of a 3D force plate horizontally positioned (Bertec FP 4060-15, Bertec Corp., USA) operating at $1000Hz$ sample rate. From this initial position ($90^\circ > \theta > 85^\circ$, measured to the horizontal plane) the rigid body was allowed to drop (Figure 32B) and the vertical and anterior-posterior $\overrightarrow{GRF}(t)$ components were recorded. Six successive trials were conducted to verify the force profile's repeatability. Data were collected using a 16 bit analogue-to-digital converter (Biopac MP 150, Biopac Systems, Inc., USA) and graphically expressed as function of time.

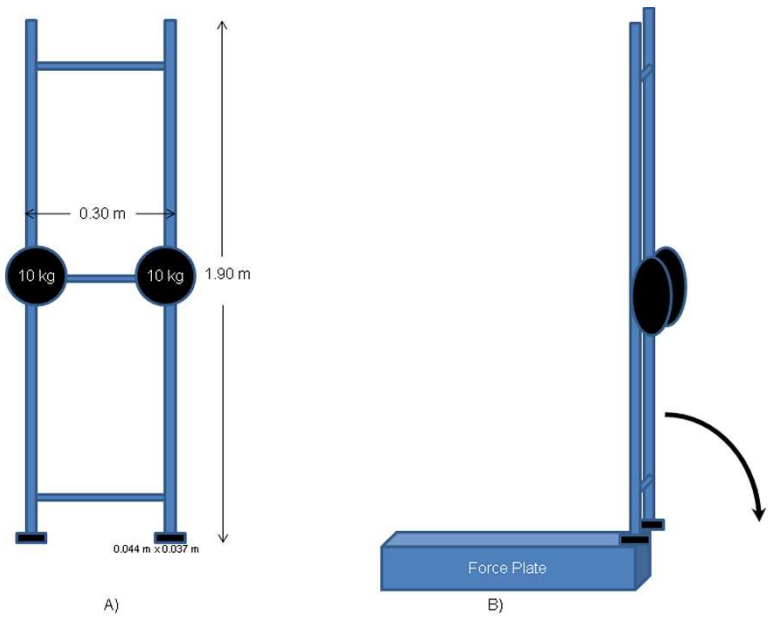


*Figure 32 Scheme of a rigid body balanced at the force plate border: frontal view (panel A) and isometric falling rotation around the medial-lateral axis that contains the centre of pressure (panel B).*

## Minimum and maximum values of inertia

Starting with a swimmer model, the minimum and maximum values of the moment of inertia around halluces ($I_{zz}$), defined by the last component of the inertia tensor matrix, were calculated and are presented below (Table 2). These values were assessed using a model of a rigid articulated body with mass $86.7kg$, volume $90.5dm^3$ and area of $3.28m^2$ compatible with two transient swimmer's inter-segmental realistic body positions assumed during the grab start: the most contracted (Figure 33 A) and the most extended (Figure 33 B) with CM-COP of $0.67m$ and $1.15m$, respectively. The expression "articulated" refers to the reality-based effective transition from the 1st to the 2nd grab start positions. The NASA (1978) human body anthropometrical inertial model was used to calculate the $I_{zz}$ values around halluces in both positions (considering the sagittal symmetry) using SolidWorks (3D CAD, DS Solidworks, Dassault Systèmes S.A., USA).

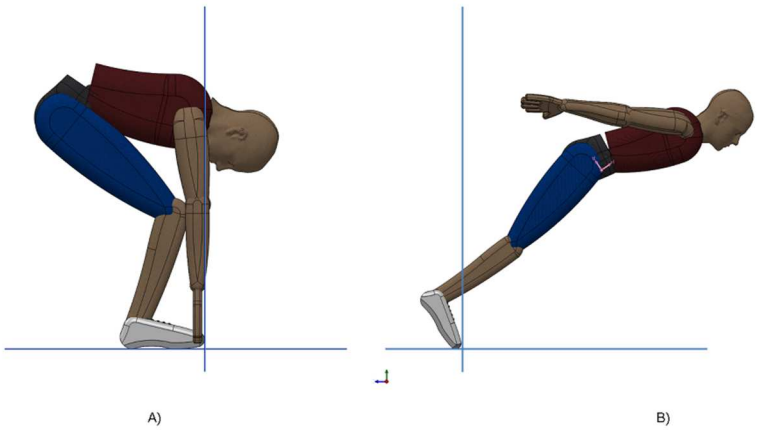


*Figure 33 Two rigid articulated body positions mimicking two limit transient body positions: the most contracted (panel A) and the most extended (panel B).*

## Mathematical model of rigid body fall

The simple rigid body falling mathematical description was conducted using the previously calculated $I_{zz}$ and the CM locus modelling. Since the motion of the rigid body is a rotation about the contact point on the starting block it is preferable to use polar coordinates.

The forces acting on the radial direction are the projection of the weight $\left(\left\|\overrightarrow{\mathrm{Proj}_{\overline{W}}}\right\| = m \cdot g \cdot \sin\theta\right)$ and the GRF, which in this work is assumed to have only a radial component. Since this force will be called the passive component, to avoid confusion with the measured GRF from the swimmer, it will be termed $R_{Passive} = \left\|\overrightarrow{R}_{Passive}\right\|$. The vectorial sum of the three forces, the centrifugal force $\overrightarrow{F_{co}}$ $\left(\left\|\overrightarrow{F}_{co}\right\| = m \cdot \frac{v^2}{r_{CM}} = m \cdot r_{CM} \cdot \omega^2\right)$, the centripetal force $\left(\left\|\overrightarrow{\mathrm{Proj}_{\overline{W}}}\right\|\right)$ and $R_{Passive}$ are in equilibrium along radial position, while in contact, whose effects may also be accounted for by the use of an accelerated referential (Figure 34), that is $R_{Passive} - m \cdot g \cdot \sin\theta + m \cdot r_{CM} \cdot \omega^2 = 0$ or, equivalently, the following statement:

$$R_{Passive} = m \cdot g \cdot \sin\theta - m \cdot r_{CM} \cdot \omega^2 \qquad (14)$$

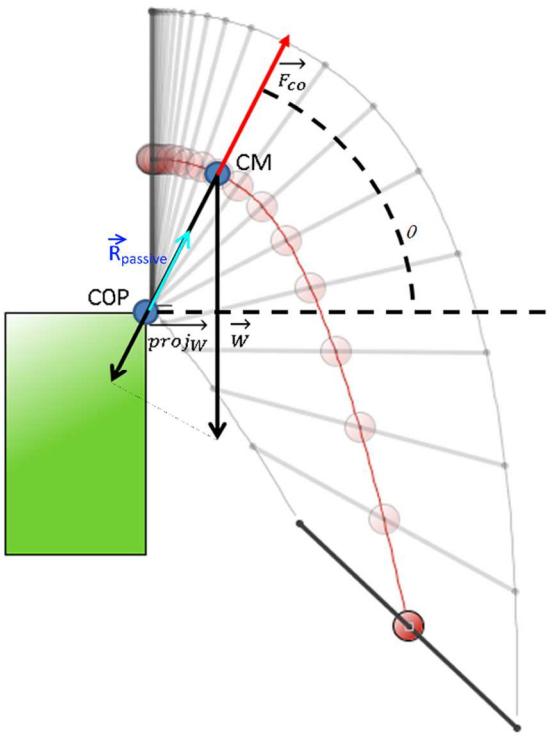


*Figure 34 Simulation of the fall of rigid body, representing θ the angle to the horizontal, COP the Centre of Pressure, CM the Centre of Mass locus, the ( $\overrightarrow{proj_{\overline{W}}}$ ) is the weight projection to the CM-COP direction, $\overrightarrow{W}$ is the rigid body weight, $\overrightarrow{R}_{Passive}$ is the ground reaction force, and $\overrightarrow{F_{co}}$ is the centrifugal force.*

For the tangential direction, the motion is better described by Newton's 2nd law in rotation form, that is $\vec{\tau} = [I] \cdot \vec{\alpha}$, where $\vec{\tau}$ is the sum of the moments of force about the rotational axis, $[I]$ is the nine components moment of inertial tensor and $\vec{\alpha}$ is the angular acceleration. In the present case the ground reaction force $(R_{Passive})$ produces no moment, as it acts on the rotation axis (COP), and the moment of the weight is due to its tangential component, that is $\|\vec{\tau}\| = \|\vec{r}_{CM} \times \vec{W}\| = r_{CM} \cdot m \cdot g \cdot \cos(\theta(t)) = \|[I] \cdot \vec{\alpha}\|$. Halluces axis shares the direction with the angular velocity $(\vec{\omega})$ and angular acceleration $\left(\vec{\alpha} = \frac{d\vec{\omega}}{dt}\right)$ vector (i.e. direction z, medio-lateral), whose expression in xyz reference axis is $\vec{\omega} = \begin{pmatrix} 0 \\ 0 \\ \omega \end{pmatrix}$ and $\vec{\alpha} = \begin{pmatrix} 0 \\ 0 \\ \alpha \end{pmatrix}$, respectively. In the grab start case, the moment of inertial tensor is practically reduced to $I_{zz}$, since the modulus of tensor product gives $\|[I] \cdot \vec{\alpha}\| = \left\| \begin{pmatrix} I_{xz} \\ I_{yz} \\ I_{zz} \end{pmatrix} \cdot \alpha \right\| \approx I_{zz} \cdot \alpha$. Since $\|\vec{\alpha}\| = \frac{d^2\theta}{dt^2} = \frac{d\omega}{dt}$ the differential equation to be solved is $\frac{d(\omega(t))}{dt} = -r_{CM} \cdot m \cdot g \cdot \frac{\cos(\theta(t))}{I_{zz}}$. To numerically solve this equation it is converted into two coupled nonlinear differential equations (Equations (15)):

$$\begin{cases} \frac{d(\omega(t))}{dt} = -r_{CM} \cdot m \cdot g \cdot \frac{\cos(\theta(t))}{I_{zz}} \\ \frac{d(\theta(t))}{dt} = \omega(t) \end{cases} \tag{15}$$

Where $\theta(t)$ and $\omega(t)$ are unknown functions of time, $I_{zz}$ is the moment of inertia around COP and one can identify the swimmers main anthropometric parameters: $m$, $r_{CM}$and $I_{zz}$. One used a Runge-Kutta method to numerically solve the equations, with initial conditions that were defined as $\omega(0)=0$ rad/s; $\theta(0)=\frac{\pi}{2}-0.001$ rad, using a modelling software (Modellus 4.01, Modellus™, Portugal and ode45 function of matlab, MathWorks).

The halluces contact line was considered as the contact locus with the starting block and deformations of the contact areas and tiny COP displacements were discarded.

The two previously obtained rigid articulated body configurations of the inertial tensor and CM position were used to assess the weight torque in the two limiting swimmer configuration (most contracted and most extended) that leads to angular position, angular velocity, angular acceleration (Equations (15)). However, contact forces and linear velocity are the observable parameters. It is possible to associate the $\overrightarrow{R}_{Passive}$ components with $\theta(t)$ and $\omega(t)$. These components are the observable (and therefore, measured) forces while in contact to ground. Equations (16) state force association while Equations (17) state position-velocity $\left(\vec{r}_{CM}, \vec{v}_{CM}\right)$respectively, vectorial association.

$$\begin{cases} R_{\text{v\_passive}} = m\cdot\left(g\cdot sin\theta - r_{CM}\cdot\omega^2\right)\cdot sin\theta \\ R_{\text{h\_passive}} = m\cdot\left(g\cdot sin\theta - r_{CM}\cdot\omega^2\right)\cdot cos\theta \end{cases} \qquad (16)$$

$$\begin{cases} \vec{r}_{CM} = r_{CM}\cdot\left(cos\theta, sin\theta\right) \\ \vec{v}_{CM} = r_{CM}\cdot\omega\cdot\left(sin\theta, -cos\theta\right) \end{cases} \qquad (17)$$

Equations (16) and (17) state for the CM kinetics and for the CM kinematics description while in contact to ground with COP as origin of the Cartesian

referential frame. The resulting movement should be a pure rotation around the COP.

Knowing that the grab start was selected due to rotations around both halluces axis, any difference of the measured contact force-time curves (incremental or decremental) during the movement compared to the passive force (Equations (17)) should be interpreted as the swimmer's active force effect.

An evidence of this model is that, as it is a pure rotation around COP, the swimmer is only able to perform forces parallel to the CM-COP segment.

## Experimental start protocol

### Ethics statement

The present study was approved by the Ethics Committee of Faculty of Sport from the University of Porto. All participants provided informed written consent before data collection. The procedures were performed according to the Declaration of Helsinki.

## Experimental measurements and analyses

Six well-trained swimmers (24.25 ± 3.61 years of age; 1.73 ± 0.08 m of height, and 68.19 ± 10.78 kg of body mass), were made fully conversant with the protocol. After a standardized warm-up, participants performed three 15 m maximal grab start repetitions (3 min resting) over a 3D force plate (Bertec FP 4060-15, Bertec Corp., USA) sampling at 1000 Hz and mounted on a special support designed to replicate a starting block used in international level competitions. A starter device (Omega StartTime IV, Swiss Timing Ltd., Switzerland) was instrumented to simultaneously produce the starting signal and export a trigger signal allowing data synchronization with the acquired $\overrightarrow{GRF}(t)$ curves and analogue-to-digital converted by a 16 bit A/D converter (Biopac MP 150, Biopac Systems, Inc., USA). The block surface angle to the horizontal

reference plane (10º) was corrected by applying a suitable rotation matrix and, therefore, vertical vs. horizontal forces were assumed rather than perpendicular vs. anterior-posterior forces.

In order to allow the comparison of the forces produced by swimmers of different masses, the forces (both the passive obtained from the model and the measured GRF from the swimmer starting motion) were divided by the respective weight.

Following the experimental protocol the active and passive from raw force splitting tool was applied. The algorithm assumes the perpendicular to CM-COP segment active force unavailability, which means that raw force leads also to a raw $\theta$ estimator. In first step, we calculate $\theta_{Raw}(t) = \text{atan}\left(\frac{GRF_v(t)}{GRF_h(t)}\right)$, where $GRF_h(t)$ and $GRF_v(t)$ are the horizontal and vertical $\overrightarrow{GRF}(t)$ components, respectively. Simultaneously, it is built the intermediate force-time variables of Equations (18).

$$\begin{cases} R_{h\_Passive\_i}(t_1) = \frac{m_{swimmer}}{m_{Model}} R_{h\_Passive\_Model}(t_1) \\ R_{v\_Passive\_i}(t_1) = \frac{m_{swimmer}}{m_{Model}} R_{v\_Passive\_Model}(t_1) \\ \theta_{Passive\_i}(t_1) = \text{atan}\left(\frac{R_{v\_Passive\_i}(t_1)}{R_{h\_Passive\_i}(t_1)}\right) \end{cases} \tag{18}$$

where $R_{h\_Passive\_i}(t_1)$ and $R_{v\_Passive\_i}(t_1)$ are the passive reaction horizontal and vertical and $\theta_{Passive\_i}(t_1)$ is the angle to the vertical. These force values are adjusted, therefore, to the mass of the swimmer but are expressed in the dependency of the unknown time $t_1$. The $\theta_{Passive\_i}(t_1)$ angle provides $t_1$ determination so that minimum of $\left|\theta_{Passive\_i}(t_1) - \theta_{Raw}(t)\right|$ at instant $t$ is reached. Figure 35A represents the stepwise algorithm for $t_1$ finding. From $t_1$ it is built

$R_{h\_Passive}(t) = R_{h\_Passive\_i}(t_1)$ and $R_{v\_Passive}(t) = R_{v\_Passive\_i}(t_1)$. In the last step, $\vec{R}_{Active}(t)$ is calculated with Equations (19).

$$\begin{cases} R_{h\_Active}(t) = GRF_h(t) - R_{h\_Passive}(t) \\ R_{v\_Active}(t) = GRF_v(t) - R_{v\_Passive}(t) \end{cases} \quad (19)$$

Figure 35 B diagram depicts the general operations done to split the active and passive from the raw force.

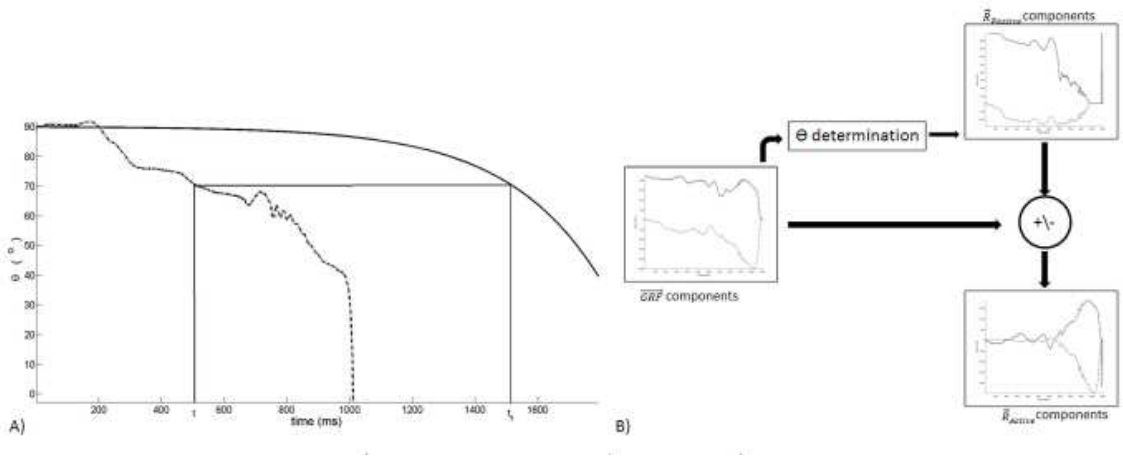


*Figure 35 . $\theta(t_1)$ determination to process the $\overrightarrow{GRF}(t)$ components to split it in $\vec{R}_{Passive}$ and the $\vec{R}_{Active}$ algorithm: graphical description with $\theta$ generated by the swimmer in dashed-dotted curve and rigid articulated body in continuous curve (panel A) and raw algorithm flowchart (panel B).*

## Statistical procedures

Pearson correlation coefficient between experimental rigid body fall and simulated were used in the vertical and horizontal force components. The three force-time curves (raw, active and passive) of each swimmer (i.e., 18 force-time curves for each pair of forces studied) were reported as mean (±s) and the variability displayed in each mean curve was assessed by the coefficient of variation.

## Results

### Physical rigid body falling and simulations

Figure 36 displays the vertical and horizontal components of the $\overrightarrow{GRF}(t)$ measured during the experimental rotating fall of the rigid body, and the respective simulation. For the experimental rotating fall, there was a quasi-stable vertical force-time curve profile up to $\sim 650ms$ and, subsequently, a monotonic force reduction until the take-off. The horizontal component displayed a stable zero value up to $\sim 150ms$ and a monotonic increase until $\sim 1150ms$, which characterizes a peak of $-74N$ (i.e., $\sim 30\%$ of the body weight considered) before the take-off. Even in the absence of any active propulsion effort, real propulsion can be observed. The force-time curves processed by means of the simulation was similar to the profile observed during the rigid body fall experiment. It was noted a quasi-stable vertical force-time curve profile up to $\sim 1300ms$ and, subsequently, a monotonic force reduction until the take-off. From the horizontal component, a stable value was displayed up to $\sim 750ms$ and a monotonic increase until $\sim 1800ms$ that characterizes a peak of $-80N$ (i.e., $\sim 30\%$ of the body weight considered) before the take-off. Correlation for the vertical and horizontal components between experimental and simulated were $0.905$ and $0.999$ respectively.

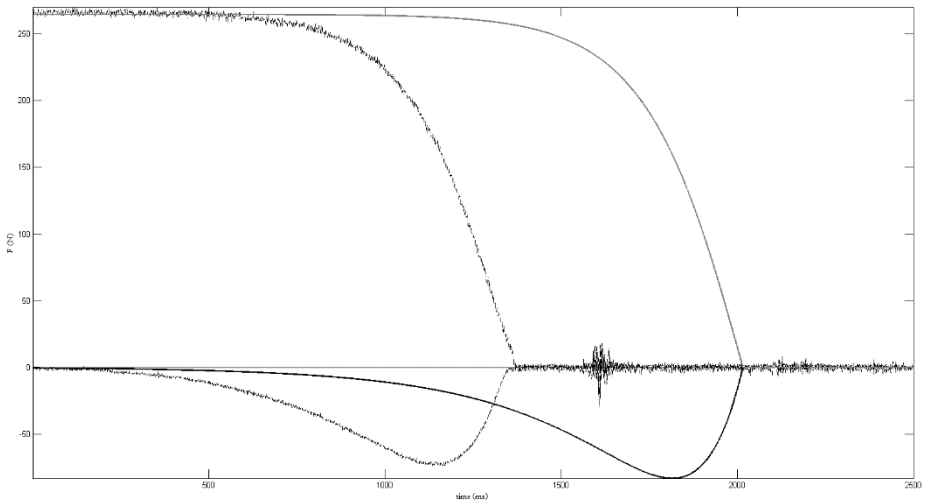


*Figure 36 Experimental rigid body falling pattern (discretized lines) and force obtained from the mathematical model of $\vec{R}_{Passive}$ (continuous line) pattern. The vertical and horizontal force components, in both cases, are represented. For clarity of representation the horizontal component has been multiplied by -1.*

The minimum and maximum inertia matrix component $I_{zz}$ obtained in the respective most contracted and extended rigid articulated body positions (Figure 33) is used to provide correction to the model considered in the rigid body fall simulation. Complete matrix components are presented in Table 3. The $I_{zz} \gg I_{yz}, I_{xz}$ justifies the non-meaningfulness of differences of $I_{yz}, I_{xz}$ values between both rigid articulated body positions. Inertia $I_{zz}$ value almost doubles from the most contracted to the most extended rigid articulated body positions.

*Table 3 Inertia Tensors (kg.m2) calculated to hallux rotation point in the two rigid articulated body positions.*

| Rigid articulated body positions | Moment of Inertia matricial components |
|---|---|
| Most contracted | $\begin{bmatrix} I_{xx} & I_{xy} & I_{xz} \\ I_{yx} & I_{yy} & I_{yz} \\ I_{zx} & I_{zy} & I_{zz} \end{bmatrix} = \begin{bmatrix} +44.6929 & -14.1389 & +0.0007 \\ -14.1389 & +8.1041 & -0.0018 \\ +0.0007 & -0.0018 & +50.8178 \end{bmatrix}$ |

| | |
|---|---|
| Most extended | $\begin{bmatrix} I_{xx} & I_{xy} & I_{xz} \\ I_{yx} & I_{yy} & I_{yz} \\ I_{zx} & I_{zy} & I_{zz} \end{bmatrix} = \begin{bmatrix} +59.6219 & +54.1270 & -0.0000 \\ +54.1270 & +55.9084 & -0.0000 \\ -0.0000 & -0.0000 & +113.2425 \end{bmatrix}$ |

Figure 37A displays the different simulations for the mathematical model for the angle $\theta$ , the blue and cyan lines for a model with 90 kg and the red and magenta for a model with 60 kg. In this panel it is obvious that the time to take-off varies with the inertial properties of the model and the starting conditions. However if we plot in the horizontal axis the time to take-off, then the models all converge to a common area, as depicted in Figure 37B.

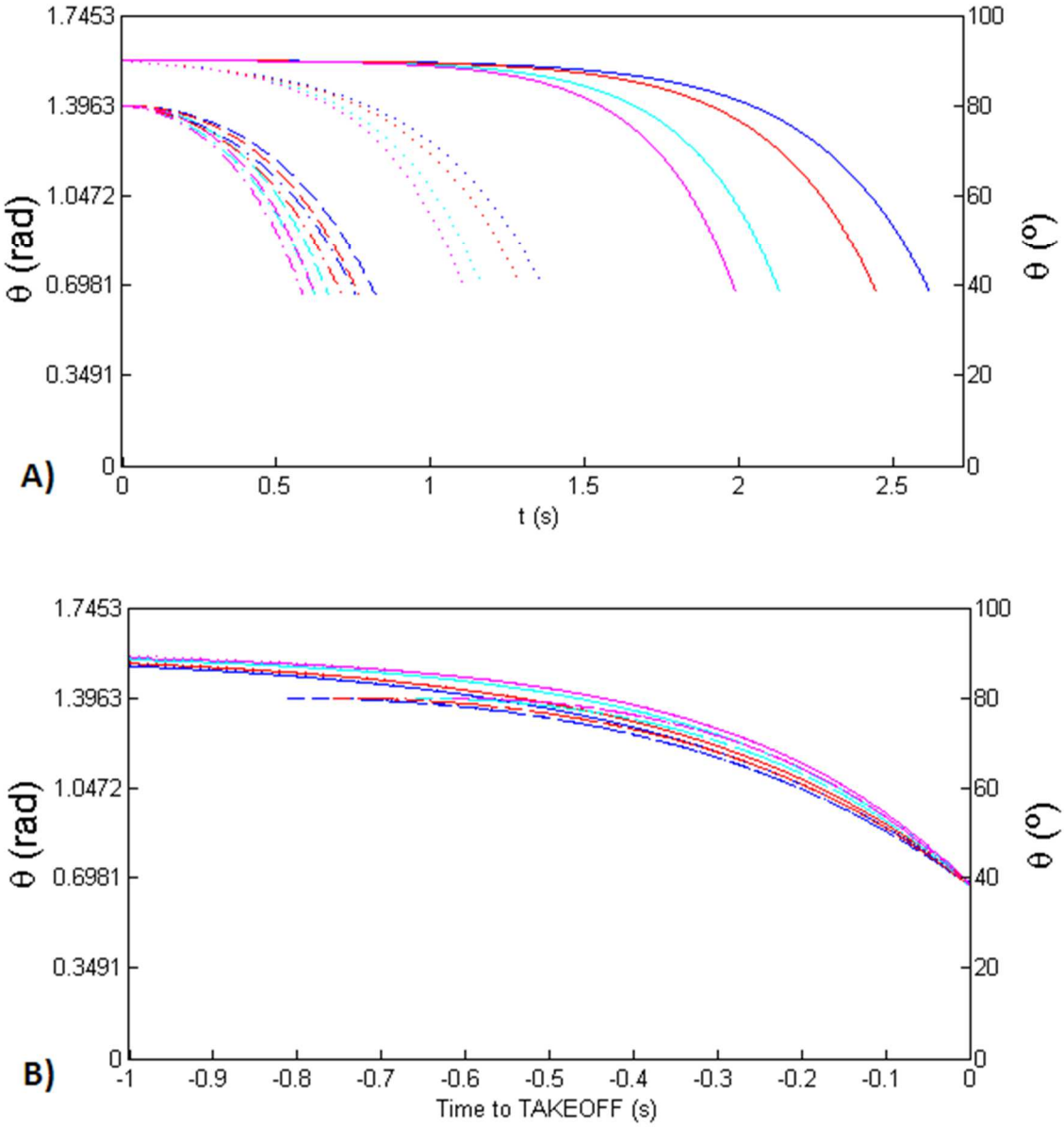


*Figure 37 Angle to the horizontal for the mathematical model of rigid body free rotating fall. In both panels the blue and cyan lines for a model with 90 kg and the red and magenta for a model with 60 kg. The initial conditions are: solid lines: θ(0)=89.9º;ω(0)=0 rad/s; dashed lines: θ(0)=80º; ω(0)=0 rad/s; dotted lines: θ(0)=90º; ω(0)=-0.1 rad/s; dash-dotted lines: θ(0)=89.9º; ω(0)=-0.1 rad/s;. In panel A the angles generated have the same initial origin time and in panel B have the same take-off instant.*

The same is true for the force, both the horizontal and the vertical, as displayed in Figure 38.

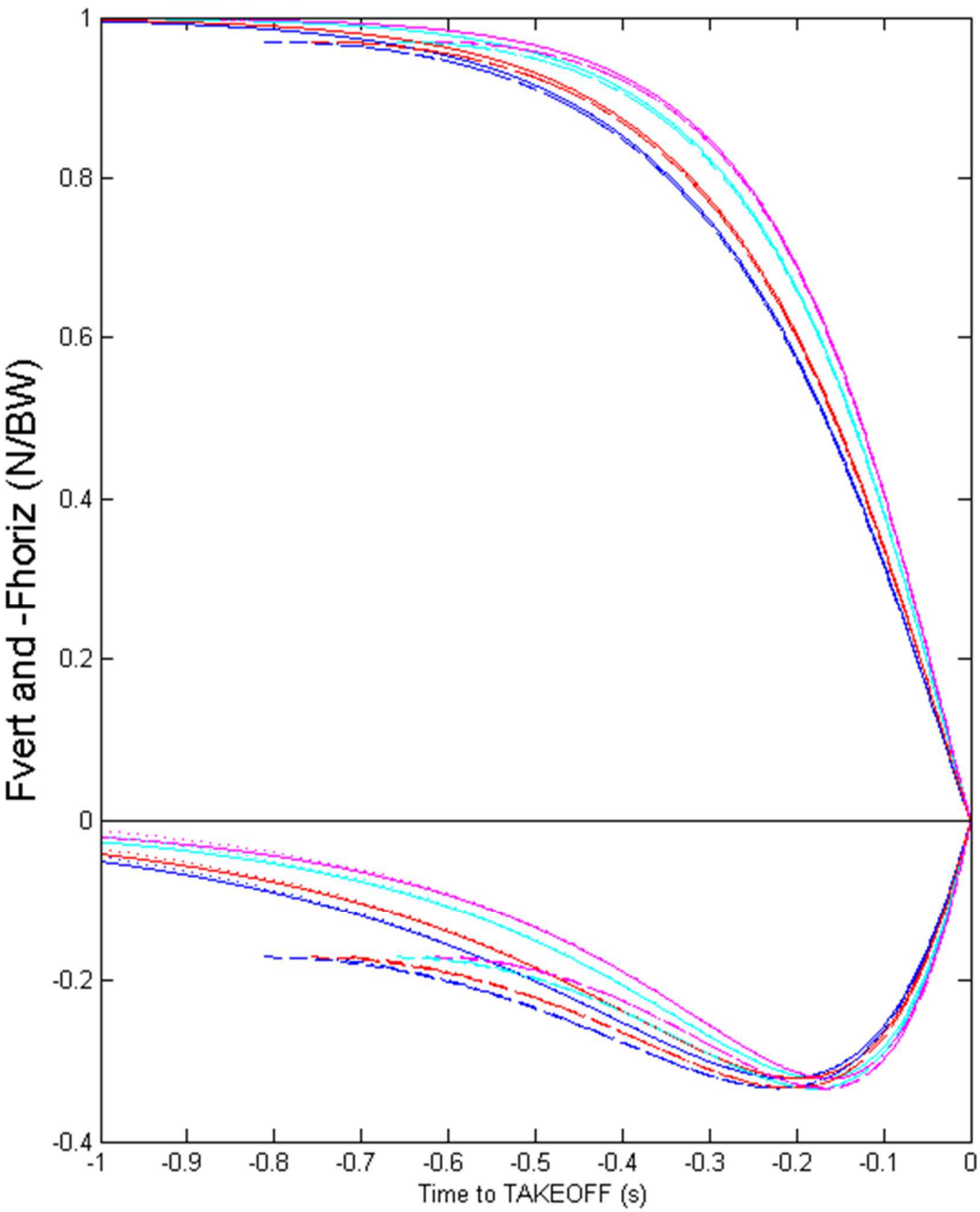


*Figure 38 Horizontal and vertical components of the force for the mathematical model of rigid body free rotating fall. In both panels the blue and cyan lines stand for a model with 90 kg and the red and magenta for a model with 60 kg. The initial conditions are: solid lines: θ(0)=89.9º;ω(0)=0 rad/s; dashed lines: θ(0)=80º; ω(0)=0 rad/s; dotted lines: θ(0)=90º; ω(0)=-0.1 rad/s; dash-dotted lines: θ(0)=89.9º; ω(0)=-0.1 rad/s;.. For clarity of representation, the horizontal component has been multiplied by -1.*

## Experimental starting protocol

Figure 39 exhibits the angles ($\theta$) generated by the swimmer $\overrightarrow{GRF}(t)$, by the most contracted and by the most extended rigid articulated body falling $\vec{R}_{Passive}(t)$ curves for the equal conditions presented in Figure 37 and Figure 38. The non-

smooth swimmer's $\theta$ curve exhibits extension values down to $\sim 0^{\circ}$, but only for short time period. The unanimated bodies presented similar $\theta$ values for take-off and pattern smoothness, and generate a range of values that does not include the swimmer $\theta$ generated, particularly in the latest values.

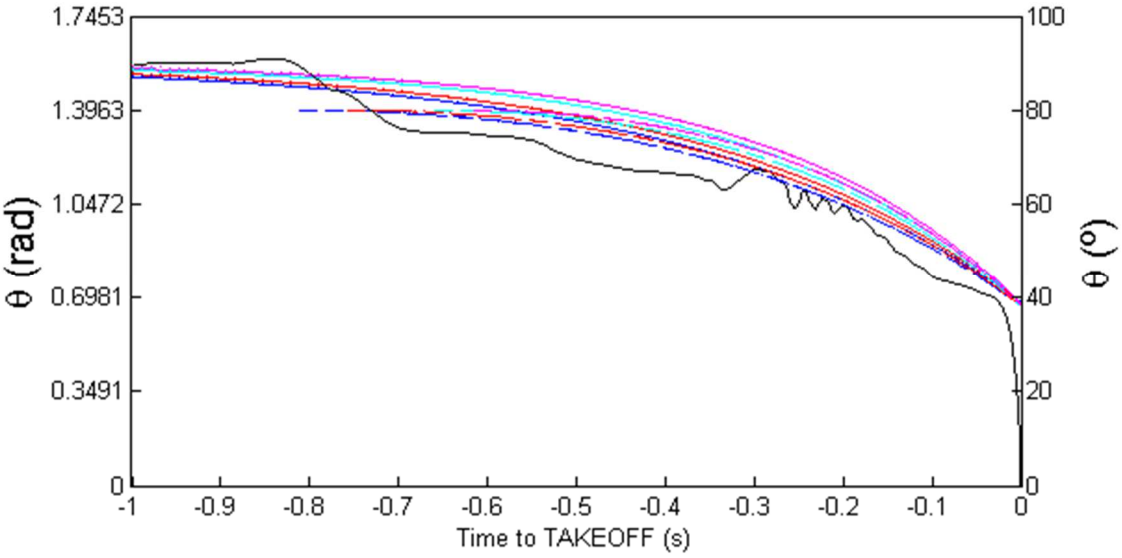


*Figure 39 Angle to the horizontal produced by the swimmer, while in contact to block (continuous black line) and angle to the horizontal for the mathematical model of rigid body free rotating fall. The blue and cyan lines stand for a model with 90 kg and the red and magenta for a model with 60 kg. The initial conditions are: solid lines: θ(0)=89.9º;ω(0)=0 rad/s; dashed lines: θ(0)=80º; ω(0)=0 rad/s; dotted lines: θ(0)=90º; ω(0)=-0.1 rad/s; dash-dotted lines: θ(0)=89.9º; ω(0)=-0.1 rad/s. The angles generated have the same take-off instant.*

The application of the previously mentioned $\theta$ mapping and determination in each of the 18 individual curves lead to the mean raw, passive and active force-time curves and respective (±sd) (Figure 40, panels A, B and C, respectively). Regarding the vertical and horizontal raw force components (Figure 40, panel A), a progressive variability was observed from $\sim 50\%$ to $100\%$ of block time and force values CV of $25.4$ and $37.8\%$, respectively. Concerning both $\vec{R}_{Passive}(t)$ components (Figure 40, panel B), the vertical force showed a progressive variability from $\sim 25$ to $100\%$ of block time and force values CV of $16.9\%$, whereas the horizontal force registered a more restrictive variability (between $\sim 50\%$ to $70\%$ of block time and force values CV of $16.9\%$). Considering both $\vec{R}_{Active}(t)$ components (Figure 40, panel C), it is verified an abrupt increase in variance from

40% to 100% of block time and force values CV of 67.9% and 66.2%, respectively. An evident symmetry between vertical and horizontal active force mean profiles is noted from the starting signal to the take-off instant (Figure 40, panel C).

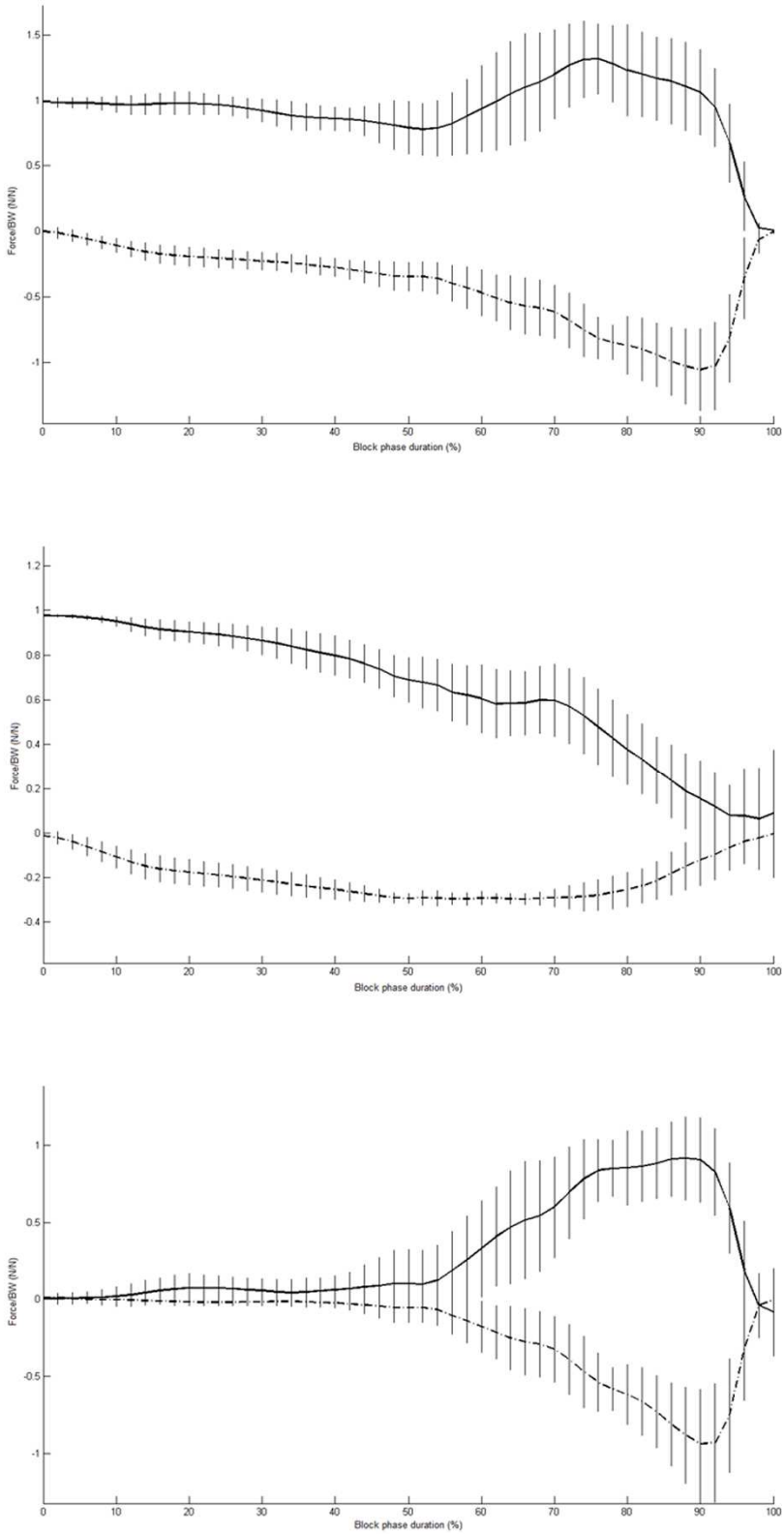


*Figure 40 Mean horizontal and vertical (dash-dotted line and continuous line, respectively) force-time curves for the grab start technique, expressed as a percentage of the time period between starting signal and the take-off instant: Raw mean forces (panel A), passive mean forces (panel B) and active mean forces (panel C). The vertical continuous bars denote the local standard variations for each force component. Force data are presented as a fraction of the swimmers' body weight (BW). For clarity of representation the horizontal component has been multiplied by -1.*

## Discussion

In swimming, the start phase is typically divided into the block, flight and underwater sub phases (Elipot et al., 2009; S. Slawson, Conway, P., Cossor, J., Chakravorti, N., West, A. , 2013; Vilas-Boas et al., 2003), with the former considered determinant since it initiates the starting action and prepares the following phases. (Vantorre *et al.* 2010). In fact, the study of the force behaviour during the block phase has received considerable attention (Vilas-Boas *et al.* 2003, Breed &Young 2003, Guimarães & Hay 1985, Galbraith *et al.* 2008, Slawson SE *et al.* 2013, Vantorre *et al.* 2010b, Lyttle & Benjanuvatra 2005), but researchers have not yet considered the study of dynamometric data based on the physics of the superposition principles, limiting its applicability to regular performance diagnosis (Holfelder *et al.* 2013). Therefore, we aimed to implement a tool to study the $\overrightarrow{GRF}(t)$ applied on the swimmers during the block phase, splitting $\vec{R}_{Active}(t)$ from $\vec{R}_{Passive}(t)$. The pathways used allowed an appropriate description of both force contributions from the raw data, confirming the hypothesis that swimmer's forces applied on the starting block are dependent on muscular based biomechanical actions and on the body weight dynamical effects. The application of the splitting algorithm led to a noticeable force variability dependence on $\vec{R}_{Active}(t)$, highlighting that swimmers' voluntary propulsion is more evident in raw $\overrightarrow{GRF}(t)$ variability than $\vec{R}_{Passive}(t)$.

The current study was conducted with three stepwise determinations with the first two (defined by the force patterns assessment during the falling rigid body) leading to model forces and variable dependencies that were achieved in the following two steps. The force-time curves displayed during the rigid body experiment were similar to the maximum vertical and horizontal force profiles observed during the simulation of the respective phenomena (correlation values, time delays, and maxima/minima values), except the added contact time due to the initial angle (Figure 36). The correlation findings for the vertical force curves are less than 0.95 due to lack of initial data, probably on account of high $\theta$ accomplishment difficulties. The horizontal peak force observed before the take-off, noticed in the force-time curves of the rigid body experiment and simulation (Figure 36), has a similar profile to that displayed in a previous ventral start study

(Slawson 2013). Swimmers seem to generate the main take-off propulsion between the most contracted and the most extended postures. While mimicking the swimmer postural segment geometries, an unanimated articulated rigid body allows the determination of moment of inertia around COP and limits their respective $I_{zz}$ values. The changes in inertia moments due to the two different inter-segmental positions (Figure 33) were used in simulations and have shown no effect in the force-time curve profiles allowing the use of $\theta = \arctan\left(GRF_v / GRF_h\right)$ as a parameter in the CM-COP direction, which was essential for the tool that separated $\vec{R}_{Active}(t)$ from $\vec{R}_{Passive}(t)$ (Figure 35). Unanimated $\theta$ curve exhibited similarity, while the swimmer's θ curve exhibits more irregularities, since the latter depends upon swimmer's muscular actions. The unanimated curves were similar because $I_{zz}$ doubles (from 50.8 to 113 kg.m2, ratio of 2.22) while $r_{CM}$ also almost doubles (from 0.67 to 1.15 m, ratio of 1.72) making Equations (16) almost invariant. Another supplemental reasoning can generate another quasi-invariance on Equations (16) taking account on the, supposedly, independent anthropometric variables. For instance, consider two ideal swimmers (or any two objects) with different body mass, ascribed $m_1$ and $m_2$ but with a similar volumetric mass and with a possible perfect 3D homothety between them. It is possible to perform a transformation between them that applies, as in Equations (20).

$$\begin{cases} L_1 \rightarrow L_2 = \sqrt[3]{\dfrac{m_2}{m_1}} L_1 \\ V_1 \rightarrow V_2 = \dfrac{m_2}{m_1} V_1 \\ I_1 \rightarrow I_2 = \left(\sqrt[3]{\dfrac{m_2}{m_1}}\right)^2 \dfrac{m_2}{m_1} I_1 \end{cases} \qquad (20)$$

Where $L$ stands for any one-dimensional quantity like $r_{CM}$, $V$ for volume and $I$ the inertia moment around COP. These transformations, taken simultaneously, leave the Equations (16) with a $\cos(\theta)$ coefficient reduced to $79\%$ if $\frac{m_2}{m_1}=2$, which is not an usual ratio, while $\frac{m_2}{m_1}=1.25$ reduces to $93\%$ from the lighter (being the faster) to heavier (being the slower) value. Bigger limb dimensions in the heaviest swimmer could, however, enable contact during time enough to produce more impulse, compensating the loss above mentioned. Equations (16) and (17) that might differ as $r_{CM}$ slightly changes, remain seemingly unchanged in function of $\theta$ . The results of the two mentioned quasi-invariances also motivate us to search what defines the anthropometric difference between swimmers (i.e., intersegment distances and distribution of masses, and specific mass strength or power).

The theta mapping methodology was implemented on a raw swimmer pattern (Figure 39) where it is observed the theoretical take-off angle reached before the unanimated curves did. That precise instant should be the matching of the overall curves and posterior force is a pure voluntary force. If the matching of the take-off angles took place then the posterior force exerted should be voluntary force. Also the anterior angle pattern would belong to the neighbourhood of the swimmer's angle take-off instant the theta earlier values belong to the neighbourhood of the other unanimated curves presented. The theta mapping methodology was also applied on raw swimmers' force patterns (Figure 40, panel A), allowing the splitting of $\vec{R}_{Passive}(t)$ from $\vec{R}_{Active}(t)$ (Figure 40, panels B and C). The raw force-time curves variability was comprised of the respective $\vec{R}_{Passive}(t)$ and $\vec{R}_{Active}(t)$ variability and it was most evidenced in the last 50% of the block time for vertical and horizontal components. This finding was expected since swimmers can effectively propel themselves out of the starting block after the hands leave the handgrips, generating greater resultant impulse with the lower than with the upper limbs (R. V. Breed & Young, 2003; K. de Jesus, de Jesus, K., Figueiredo, P., Gonçalves, P., Pereira, S. M., Vilas-Boas, J.P., Fernandes, R.J.,

2011; Galbraith et al., 2008; Guimaraes & Hay, 1985; Lyttle & Benjanuvatra, 2005; S. Slawson, Conway, P., Cossor, J., Chakravorti, N., West, A. , 2013). In fact, $\vec{R}_{Active}(t)$ components also displayed an increased variability from the $40\%$ of the block time, seeming to be the major contributor to the raw variability. The main swimmer's task has environmental and organism constraints are faced during the most propulsive block instants and subtle differences may distinguish swimmers and swimmers' trials as a consequence of environmental changes, training procedures or learning phenomena (Preatoni et al., 2013). In contrast, the $\vec{R}_{Passive}(t)$ components are dependent on swimmers' structure and inertial components, reducing the degrees of freedom involved in swimming start movement and, the consequential variability.

Despite the noticeable contribution of the $\vec{R}_{Active}(t)$ components to the raw force-time curves variability, it should also be considered as their symmetric profile registered from the starting signal to the take-off (Figure 40, panel C), which could indicate a $\sim 45^{\circ}$ declination body steering intention. In fact, since the starting signal, swimmers seem to compensate the vertical force reduction as a strategy to falling in a controlled vertical speed, allowing the best angular determination for explosive force during the take-off instants. Force-time curves observed in other swimming start techniques have already displayed qualitatively this symmetry in raw data (Slawson *et al.* 2013), but no further clarification was exhibited. Several previous raw $\overrightarrow{GRF}(t)$ research findings may lead to a misunderstanding of the real muscular action measurement. The current study evidences the need to consider $\vec{R}_{Active}(t)$ and $\vec{R}_{Passive}(t)$ components to avoid the raw force-time curves masking effects.

Notwithstanding the study's originality and relevance, some limitations and future research directions should be considered. Firstly, the mathematical model applied still lacks a refined description of part of the rotational angular velocity impact, since the COP might have tiny anterior-posterior movements that were not considered; this indicates the need to include angular positioning and angular velocity mappings for the rigid articulated body passive reaction calculations, particularly knowing that slight angular changes in the beginning can substantially reduce block contact times. We should point out that $\omega$ cannot vary randomly

and has peak values constraints (taking account of its influence in Equations (17) and (18), which could limit its instantaneous variance, avoiding some of the noticed ringing in $\vec{R}_{Passive}(t)$. This might be an improvement in the development of future algorithms. Secondly, as the lateral responsiveness was not considered, its consistent assessment is recommended to provide detailed dynamometric information for proper forces direction achievement. Calculations could lead to inertial tensor components of mimicking rigid articulated body positions, considering a brand new segment arrangement compatible with the track start, which is also a very commonly used technique. This inertial tensor would lack the proposed grab start sagittal symmetry, and would have, theoretically, dependency on time, but further studies could reveal its minimum and maximum values and how rotation around the hallux would change its dynamical behaviour. The segment arrangement with its origin in the front limb (when rear lower limb takes off) combined with initial angular velocity could lead, once again, to separating assessment, since CM to COP segment and subsequent former grab start considerations could be applied. Future studies should include different intersegmental compatible rigid articulated body transient swimmer's inter-segmental in ventral and dorsal realistic start body positions to map more $I_{zz}$ values.

## Conclusions

This is the first study that has implemented a tool to analyse the active and passive vertical and horizontal reaction forces applied by the swimmers during the block phase of a grab start. Experimental events and simulations have confirmed the passive contribution on raw force data and have allowed the separating of the active force component from the swimmers' force-time curves. The active forces seem to strongly contribute to the raw force variability and denote a vertical and horizontal symmetric profile characteristic of the optimum projection angle to obtain a maximal horizontal displacement range. Future research should consider the active and passive force profiles in different starting techniques for performance advances and aid diagnostics for coaching.

**Acknowledgments**

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## References


Breed, R. V., & Young, W. B. (2003). The effect of a resistance training programme on the grab, track and swing starts in swimming. *Journal of Sports Sciences, 21*(3), 213-220.

de Jesus, K., de Jesus, K., Figueiredo, P., Gonçalves, P., Pereira, S. M., Vilas-Boas, J.P., Fernandes, R.J. (2011). Biomechanical analysis of backstroke swimming starts. *Int. J. of Sports Med., 32*, 546-551.

Elipot, M., Hellard, P., Taïar, R., Boissière, E., Rey, J., Lecat, S., & Houel, N. (2009). Analysis of swimmers' velocity during the underwater gliding motion following grab start. *Journal of Biomechanics, 42*(9), 1367-1370.

Galbraith, H., Scurr, J., Hencken, C., Wood, L., & Graham-Smith, P. (2008). Biomechanical comparison of the track start and the modified one-handed track start in competitive swimming: An intervention study. *Journal of applied biomechanics, 24*(4), 307-315.

Guimaraes, A. C. S., & Hay, J. G. (1985). A mechanical analysis of the grab starting technique in swimming. *International Journal of sport biomechanics, 1*(1), 25-35.

Holfelder, B., Brown, N., & Bubeck, D. (2013). The influence of sex, stroke and distance on the lactate characteristics in high performance swimming. *PloS One*(8). doi: 10.1371/journal.pone.0077185

Lyttle, A., & Benjanuvatra, N. (2005). Start Right–A Biomechanical Review of Dive Start Performance. *Zugriff am, 15*.

Mason, B., Mackintosh, C., & Pease, D. (2012). *The development of an analysis system to assist in the correction of inefficiencies in starts and turns for*

*elite competitive swimming.* Paper presented at the ISBS-Conference Proceedings Archive, Melbourne: Australian Catholic University.

NASA. (1978). *Anthropometric source book.* (Vol. Volume I: Anthropometry for designers. ): Ohio: Yellow Springs.

Preatoni, E., Hamill, J., Harrison, A. J., Hayes, K., Van Emmerik, R. E., Wilson, C., & Rodano, R. (2013). Movement variability and skills monitoring in sports. *Sports Biomechanics, 12*(2), 69-92.

Seifert, L., Vantorre, J., Chollet, D., Toussaint, H. M., & Vilas-Boas, J.-P. (2010). Different profiles of the aerial start phase in front crawl. *The Journal of Strength & Conditioning Research, 24*(2), 507-516.

Slawson, S., Conway, P., Cossor, J., Chakravorti, N., West, A. . (2013). The categorisation of swimming start performance with reference to force generation on the main block and footrest components of the Omega OSB11 start blocks. *Journal of Sports Sciences, 31*, 468 - 478.

Vantorre, J., Seifert, L., Fernandes, R., Vilas-Boas, J., & Chollet, D. (2010a). Kinematical profiling of the front crawl start. *International journal of sports medicine, 31*(01), 16-21.

Vantorre, J., Seifert, L., Fernandes, R., Vilas Boas, J., & Chollet, D. (2010b). Comparison of grab start between elite and trained swimmers. *International journal of sports medicine, 31*(12), 887-893.

Vilas-Boas, J. P., Cruz, J., Sousa, F., Conceicao, F., Fernandes, R., & Carvalho, J. (2003). *Biomechanical analysis of ventral swimming starts: Comparison of the grab start with two track-start techniques.* Paper presented at the Biomechanics and Medicine in Swimming IX, Saint-Étienne, France.

# Chapter 5

## Ground Reaction forces produced in Relay changeovers – Active Force assessment in Track Start

In competitive swimming, there have been few studies on relay start techniques (McLean, Holthe, Vint, Beckett, & Hinrichs, 2000) and some of them have analyzed different starting techniques (no-step or conventional, single-step and double-step). Findings revealed that the step starts involved longer exchange block times than no-step starts (T. Takeda *et al.*, 2010) and the effective use of the double-step starts depends on the swimmers' ability to take longer steps (McLean *et al.*, 2000) Despite FINA rules allow the 2nd, 3rd and 4th swimmers to be in motion on the starting platform before their incoming teammates have finished their segment of the race, the track start technique is still adopted by those swimmers as a changeover technique (Saavedra *et al*., 2014). In fact, some teams are more conservatives, so as to avoid disqualification, they increase exchange block time. In this context, the aims of this chapter were two-fold: (i) to characterize the kinetics of the most used of the swimming changeover relay techniques (including the track start), and (ii) to implement a previous developed algorithm to split the passive from active forces generated during the track start technique performed in individual condition. The second aim seems pertinent since it is supposed that the last singular limb contact force pattern during tenths of second have similarities to grab start in the way that Centre of Pressure (COP) remains static in the edge of the block and propulsion is applied in the COP to Centre of Mass segment (Formicola & Rainoldi, 2015).

## Chapter 5.1

### Force-profile characterization generated in four different changeover relay start techniques

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**Abstract**

Studies on swimming start techniques have included kinetics for performance characterization in one of the utmost important phases of the start technique: the

block phase. Although there are many studies on this subject on ventral and dorsal individual starts, they are scarce on relay changeovers. This work provides ground reaction force pattern description of four changeover techniques: traditional, conventional or no-step, single step, double step, and track start. This data also materialized the full use of the capabilities of one novel dynamometric device, addressing simultaneously the ventral starts dedicated platforms (with the handgrips) and the underwater force plates (which were developed in another project). Eight national level competitive swimmers (19.9 ± 5.3 years of age; 72.5 ± 11.3 kg body mass; 1.78 ± 0.04 m height) randomly performed three times each one of the above referred four relay changeover techniques. Swimmers started, in changeover conditions, from an instrumented starting block with seven tri-axial synchronized waterproof force plates (including two underwater for arriving assessment) to perform a maximal 15 m sprint. Results demonstrates the uniqueness of this device for monitoring swimming starts, evidencing for the first time the three components of the force to time curve of each one of the swimmers' limbs in contact with the block in each one of the starting techniques. Qualitative analysis were conducted, showing that force patterns are signatures of each studied technique. This study also showed the potential of the novel dynamometric device used, and gave hints for future data processing procedures, and software enhancements.

Keywords: *biomechanics, kinetics, ground reaction forces, swimming, relay events*

## Introduction

The start is the fastest phase of a swimming race, and its effective performance is an essential part of competition, particularly in shorter distance events (Tor, Pease, & Ball, 2015; Vantorre, Cholet, & Seifert, 2014). This leads biomechanists to invest in new methods (L Mourão et al., 2015) and technologies (S. Slawson, Conway, P., Cossor, J., Chakravorti, N., West, A. , 2013) for detailed kinematic and kinetic studies (L Mourão et al., 2015). Starting actions are used in individual and relay events, differing by the starting stimulus, being the former auditory and the latter visual (Vilas-Boas et al., 2003). The individual ventral starts have been often studied, compared to the backstroke and relay starting techniques, which might be justified by the higher quantity of official individual ventral events (K. de Jesus, de Jesus, Fernandes, Vilas-Boas, & Sanders, 2014a), as well as by the higher complexity that relay experimental conditions require (*e.g.,* two swimmers, one of them arriving and the other one starting in a real start condition) (McLean et al., 2000).

The freestyle and medley relay teams are comprised of four swimmers, each one swimming one-fourth of the prescribed distance (Gambrel, Blanke, Thigpen, & Mellion, 1991). The first swimmer must abide the rules governing the start for the individual events and the remaining swimmers may be in motion at the start stimulus – the contact of the arriving swimmer as stated in SW10.11 (FINA, 2014). Indeed, the latest swimmers must maintain at least one foot in contact with the starting platform at the time the preceding swimmer touches the arriving wall. FINA's swimming rules in relay changeover allows the starting swimmer to anticipate the finishing touch (SW 10.11 (FINA)), developing most of the on block

starting actions before it actually happens, implying great accuracy of the measurement device. In relay events, the responsibility of a good start is shared between the incoming and outgoing swimmers (Gambrel et al., 1991; Saavedra et al., 2014), and the incoming swimmer's responsibility is to finish in a predictable and practiced manner, which should be obvious to the outgoing swimmer.

From the 60's to the beginning of the 90's, swimmers used the conventional or traditional technique, which involves the arms swing and a parallel and forward positioning of the feet at the front edge of the starting block (Gambrel et al., 1991; McLean et al., 2000; T. Takeda et al., 2010). From then on, new starting techniques were adopted, included swimmers taking single or double steps before jumping with both feet ahead at the block front edge. The step start (single or double step) is considered a more difficult technique than a start involving no steps at all, because swimmers often miss the proper placement of their foot on the edge of the starting block (Gambrel et al., 1991; T. Takeda et al., 2010). Gambrel et al. (1991) measured the time needed to reach a point 10 m beyond the starting block from the instant of the take-off and concluded that the steps were equally effective as traditional starts. McLean et al. (2000) suggested that step starts offered some performance improvements over the conventional start, but these improvements were not widespread and in the case of the double-step start, were dependent on the ability to take longer steps. T. Takeda et al. (2010) were the first group which implemented kinetics of three different relay starting techniques, although only to calculate the take-off velocity and angle, and mentioned that the no-step technique gives the swimmer the fastest exchange block times.

Despite the relevant contribution of previous studies, the most propulsive force components were not assessed yet, which is necessary to reveal how swimmers generate movement in static and in-motion relay changeover conditions. Data about how well swimmers distribute the anterior-posterior and vertical force components indicates the proper take-off angle for maximum flight distance achievement. It is stated that swimmers should assume a compromise between a long time spent on the block to create more impulse and short time on the block to minimize the time deficit (Seifert et al., 2010).

This study aimed to characterize the force time curve profile of the conventional or no-step, one-step or single step, two step or double step (McLean et al., 2000; Saavedra et al., 2014) and track relay changeover start techniques.

## Method

*Participants*

Eight male competitive swimmers (19.9 ± 5.3 years of age; 72.5 ± 11.3 kg body mass; 1.78 ± 0.04 m height), volunteered to participate. All participants were healthy (no serious injury or illness occurred in the last six months), able-bodied and had participated in national level relay competitions. The local Ethics Committee approved the present study and all procedures were in accordance with the Declaration of Helsinki regarding human research. Swimmers and parents and/or guardians (when subjects were under 18 yrs.) provided informed written consent before data collection. Participants had previous experience with no-step (Figure 41, A panel), one-step (Figure 41, B panel) , two step (Figure 41, C panel) and track start techniques (Figure 41, D panel) during relay events, although preferred start technique varied between subjects (5 used the no step,

2 used the single-step, and 1 used the double step). All swimmers were able to train at their own clubs the different alternative techniques during, at least, a two weeks period, with no prejudice for previous experiences to allow selection of the preferred mode.

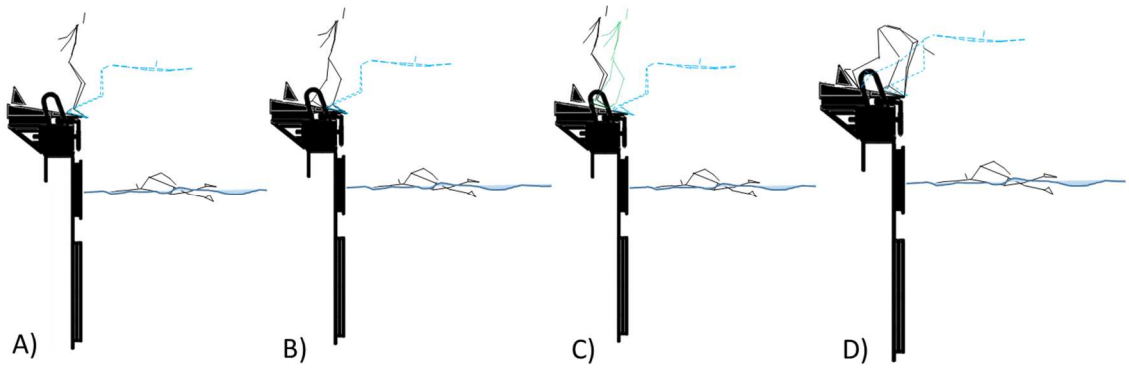


*Figure 41 Schematic representation of the various relay changeover starting techniques studied: A) Conventional or no step; B) Single or One step; C) Double or Two step; D) Track start.*

*Testing protocol*

After being measured (height and body mass) and answered a questionnaire about their training and competitive background, swimmers performed a standardized warm up consisting of 400 m front crawl based on their normal pre-race routine (Barlow, Halaki, Stuelcken, Greene, & Sinclair, 2014), followed by a familiarization period with each of the relay start techniques studied (Nguyen, Bradshaw, Pease, & Wilson, 2014). Testing sessions took place in a 25 m indoor and heated (27ºC) swimming pool, and swimmers were required to attend one testing sessions of ~1h to randomly perform 12 x 15 m maximal repetitions (being three if each relay start technique), with a resting period of about 3 min, over a new instrumented starting block with 7 x 3D6DOF dynamometric device, sampling at 2000 Hz, and FINA's facilities rules design compliant (FR 2.7).

*Data collection*

The instrumented starting block designed integrates seven triaxial waterproof extensometric force plates (adapted from Roesler et al. (2006) design) with the following locus distribution: three fixed on the top of the block (300 Hz and 200 Hz resonance frequency, according to type of platform), two laterally fixed (300 Hz resonance frequency) with two pairs of independent handgrips fixed each one on each force plate top, all of them anchored on a special built starting block, and two force plates (200 Hz resonance frequency) vertically fixed on a special built starting pool wall support. With those seven force plates, it was possible to measure independent upper and lower limb force-time curves of a swimmer over the force plates and to determine the instant of a incoming swimmers touching the arriving wall. Dynamical calibration of each force plate followed the same steps proposed by L Mourão et al. (2015) and revealed homogeneity of results for static calibration. Upper and lower limb forces were resolved into horizontal and vertical components, despite the starting block inclination.

The sampling data was 24 bit AD converted by 13 x NI 9237 modules, 4 channels each, distributed in two chassis NI 9188 (Ethernet connection) and NI 9172 (USB connection), being both devices from National Instruments Corporation (NI, USA). Synchronization between racks was guaranteed by record of an independent trigger information acquired synchronously with other channels. A mute starter device (ProStart, Colorado Time Systems Corporation, Colorado, USA) was instrumented to produce trigger signal, allowing data synchronization between racks. An overall channel selector acquisition data system was used (home implemented, using LabVIEW, National Instruments Corporation, USA

(NI)) in order to save a 8 s record (± 4 s neighbourhood of the centred to trigger time window signal), 2 kHz sample rate, 44 channels with full offset capabilities, ~ 8 Mb HD space. This period of time was referenced to the arrival of the incoming swimmer (~10 m further away from the starting wall). The dynamometric starting block directly measures vertical vs. anterior-posterior forces rather than perpendicular vs. block plane forces, once force plates were horizontally mounted and a system of edges provided the 10º inclination of the regular starting block. The recorded data were post-processed with home-implemented MatLab (MathWorks Inc, USA) matricial transfer function routines followed by the use of Bionica MatLab routine.

*Data analysis*

From each of the platform data, peak curve correlation has been searched automatically to provide maximum curve resemblance. Subsequent match of fall to zero force curves has been applied (as the pre-event of force zero contains all limb contact history). With this curve 'synchronization' algorithm, curves were normalized to BW and curve cutting has been done to minimum data sample size curve into consideration and Bionica MatLab routine has been applied.

*Statistical analysis*

Data from each force plate of each force component (i.e. horizontal and vertical) were presented as mean and standard deviation (24 force-time curve for each relay start technique).

## Results and Discussion

To our knowledge, this is the first study that presents the horizontal and vertical force curve profile of each upper (for track start only) and lower limb of the main relay changeover swimming start techniques (Figure 42 A to H panel). The force profiles are usually assessed in individual events start techniques as they can reveal the swimmers' movement proficiency (Cossor et al., 2011; S. Slawson, Conway, P., Cossor, J., Chakravorti, N., West, A. , 2013; Tor et al., 2015).

The conventional or no-step start showed very symmetrical contralateral horizontal components, almost superimposable. Meanwhile, the vertical component expressed a tendency for an initial weight support predominantly over the right foot, followed by a higher force application of the left one, perhaps traducing the dominant laterality of the subjects. Nevertheless, in all the other techniques, the leading limb seem to be the right one.

Indeed, the one step technique showed that the right foot was chosen to stay at front (interestingly the one that, for the same sample provide the higher force value in the conventional start), while the left foot steps from the rear block to the front edge. The initial impulse phase of the back foot starting the step forward is clearly visible between ~-1.25 and ~-0.5s to the take-off in both horizontal and vertical components, but particularly in the late. The final impulse of both feet is clearly synchronous in x and y components but, interestingly, the stepping foot is unable to produce vertical force comparable to the contralateral one, probably due to difficulties in weigh transfer between feet, reduced contact time, as well as

to complexity of the task itself. The horizontal component also shows that the support feet produce slight negative results during contralateral stepping, perhaps as a mechanics of CP forward displacement control. The difficulties probably associated to task complexity for force production in step starts is emphasised on the two-step technique, where the first foot to reach the front edge (the right one, again) was unable to produce similar values to the equivalent action on the one-step, and the final stepping foot, almost do not apply vertical force at all over the starting block.

Motor control capabilities of the feet positioning and subsequent impulse at such a reduced contact surface, might compromise the force generation / application capabilities of the swimmers (T. Takeda et al., 2010)).

In the track start the sample also selected the right foot as the leading one (forward foot, the last to take-off), allowing x and y peak values comparable to those provided by the conventional technique in each foot. So, the final contact vertical action of the track start shows a tendency for being less intense than the conventional one, once it is produced only by one limb. However, during part of the final force application of the right forward foot, the left back positioned one was still applying relevant force until losing contact, very close to block clearance, which may reduce the possible disadvantage of the track start in this particular. It is worthy to state that the initial position weight shift towards the forward right foot demonstrate that the majority of the swimmers uses, in relay events, a track start technique with the CM forward projected, but with inter-subjects high variability. With the start progression, the strong vertical action applied by the rear foot reduces this vertical force shift to the forward foot, which will be progressively regain during back foot take-off and final impulse of the forward one.

Still about the track start is worthy to underline the kinetics associated to the hands. When the swimmer initiates the starting action the hands force horizontal component is oriented backwards over the block, being the reaction force measured oriented forward accordingly to the action of the foot. On the contrary, the vertical action is oriented upward, with reaction forces pushing the swimmer downward, possibly reinforcing the clockwise angular momentum of the body induced by the lower limbs action. Very interesting is the perceived tendency for higher vertical force applied by the left hand, the one of the same side of the backward positioned foot.

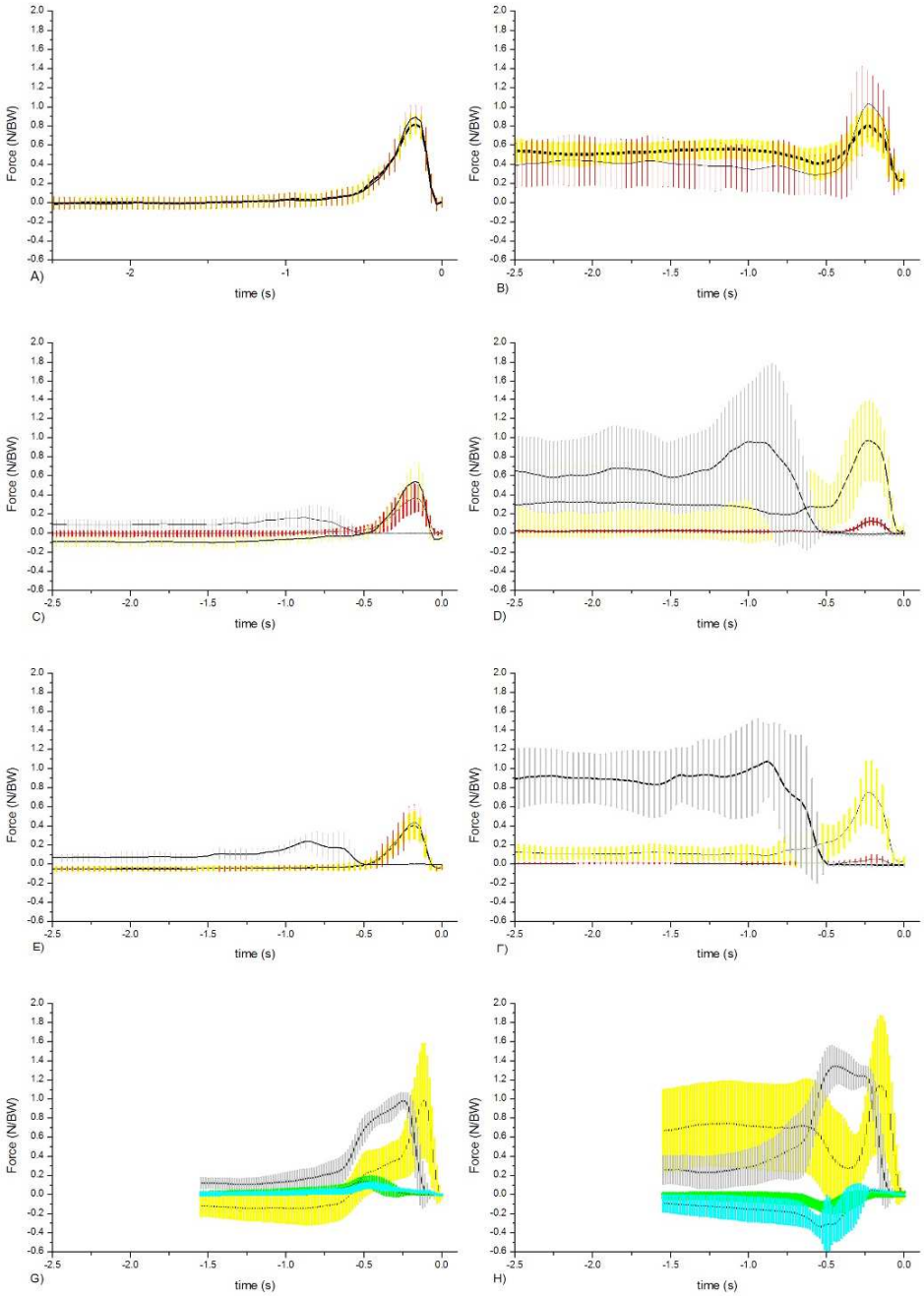


*Figure 42 Representation of the force-time curves presented: by technique (rows) – respectively: conventional, single step, double step, track start; by force component (anterior-posterior – x - left column, and vertical - y - right column), and by limb (right hand, green; left hand, cyan; rear foot, gray; front right foot, yellow; front left foot, red). In the track start row front force records (right and left) were added, as some swimmers stepped on both front platforms simultaneously (yellow curves).*

Synthesising the qualitative comparison of the kinetic signatures of the different changeover starting techniques, it might be stated that the one- and two-step in-motion starts seem to be so complex to perform that might compromise force application both in x and y axis, and particularly in the late during the final action of the end stepping foot. Indeed, some of the force peaks (Table 4), by itself, can evidence this apparent disadvantage, when they are compared to the conventional and the track start techniques. This possible handicap, however, can be at least partially compensated by the previously acquired momentum of the swimmer during the one or two step starts.

*Table 4. The peak force (N/BW) by technique, by limb, and by force component: horizontal (x) or vertical (y).*

| | **Changeover technique** | **Left lower limb** | **Right lower limb** | **Rear lower limb** | **Left upward limb** | **Right upward limb** |
|---|---|---|---|---|---|---|
| **X** | *Conventional* | +0.83±0.21 | +0.72±0.12 | - | - | - |
| | *One step* | +0.35±0.15 | +0.53±0.16 | +0.15±0.10 | - | - |
| | *Two step* | +0.4±0.22 | +0.4±0.20 | +0.25±0.08 | - | - |
| | *Track Start* | +0.91±0.21 | | +0.90±0.45 | +0.1±0.05 | +0.15±0.09 |
| **Y** | *Conventional* | +1.02±0.33 | +0.81±0.27 | - | - | - |
| | *One step* | +0.10±0.03 | +0.95±0.50 | +0.93±0.58 | - | - |
| | *Two step* | +0.075±0.04 | +0.72±0.27 | +1.05±0.27 | - | - |
| | *Track Start* | +1.12±0.68 | | +1.31±0.27 | -0.10±0.08 | -0.30±0.27 |

Comparing now the conventional and the track start, it should be emphasised that the $x$ and $y$ right and left peak force values summed are very similar, with a slight advantage for the track start (despite the observed variance hardly allow

to valorise). Moreover, in this technique they are produced in sequence, allowing a slight tendency for a longer application of force, reinforced by the hands action, which, in total, may allow higher impulses (not calculated in this study).

Another interesting finding of this study was that in all studied techniques can be noticed that peak horizontal force component of each lower limb apparently succeeds to the respective vertical component peak. Despite no published study has characterized forces in relay changeover techniques, this behaviour was already observed for the track start performed in individual events (S. Slawson, Conway, P., Cossor, J., Chakravorti, N., West, A. , 2013). Such result can be explained by the on-fall best angle of propulsion imposing the later higher horizontal force compared to the vertical one (L Mourão et al., 2015). This previous study showed that flight of inertial bodies begin at ~40º, showing that strong active propelling forces should occur at that angle as the last contact forces done and when passive forces are reduced. The current results suggest that this angle can worth more research investment, in order to evidence that surpassed the limit angle of passive force, the peak of active force could be achieved.

The above-mentioned peaks can be better summarized in Table 4. As can be seen, the highest value of the mean vertical force peak was obtained in the conventional or no step changeover starting technique, where the highest variance was also observed, perhaps just surpassed by the one step rear force vertical component. In this parameter, peaks of up to 180% of the BW were achieved and variability ranked maximum in the vertical component. Similar peak values were only obtained for the track start forward foot final action. Similar relative force peak values were previously made available in literature (Cossor et

al., 2011; S. Slawson, Conway, P., Cossor, J., Chakravorti, N., West, A. , 2013; T. Takeda et al., 2010). One step and two step changeovers are described by similar horizontal anterior-posterior force component profile (a little smaller in the two step case). The vertical component of the two step start exhibits an early high rear value (but lower than 1 BW), and low front value (though not zero). In a technique that is supposed to begin from feet positioned at the rear of the starting block, the presence of the backplate on it might force the load to be distributed not only at the rear force plate, but also the toes loading the front platforms, explaining the above referred finding.

It was also observed that, from no step, passing by single step and ending on double step, left limb (the last moving limb) vertical force component reduces, in substance, from 1.0 to 0.1 and 0.075 N/BW, successively. This suggest that the complexity of the stepping action in such a short surface may compromise the coordinative arrangement (Gambrel et al., 1991; McLean et al., 2000) underpinning the production of force by the lower limb that lastly reaches the front edge of the starting block. Further investigation is needed to support this assumption, but the lower vertical force values consistently found should concentrate the attention of scientists and coaches.

Another interesting issue appears from the apparent effectiveness of the force applied (particularly the vertical). It was made evident that conventional changeover starting technique allows higher peak values, while single step and double step reduce the peaks by any or by the combination of both of the following reasons: (i) for the same speed, values of applied force should be naturally reduced (L Mourão et al., 2015), and (ii) for CM rotation around COP in last contact on block surface area, swimmer projects his CM in an anterior-posterior

direction obviating less vertical propulsive force. This can be explained by an intentionally descending CM trajectory, imposing to smooth CM lowering and decreasing the applied vertical force.

Another interesting finding already underlined in literature (McLean et al., 2000; Saavedra et al., 2014; T. Takeda et al., 2010), is that the area below the curves are related (particularly the anterior-posterior component) to the same velocity component. This also explains the 'lowering' force values of these curves across the different techniques, as starting to move earlier introduce higher speed, diminishing the contact time particularly in the most propulsive last few instants.

**Conclusions**

The main aim of this work was to describe the force-time curves of the most used starting techniques in relay changeovers. Such task had to be undertaken with a dynamometric central capable of limb individualized force assessment.

This study highlighted the external kinetic specificity of the studied relay changeover techniques dictated by the different kinematical structure of each one.

The step techniques tended to show lower anterior-posterior and vertical peak force values than conventional and track techniques. This is probably related to the stepping feet lower contact time and task complexity.

Out of this study further research on changeover starting techniques should be conducted, relating impulse, subsequent swimmer's kinematics, and performance.

**Acknowledgments**

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## References


Barlow, H., Halaki, M., Stuelcken, M., Greene, A., & Sinclair, P. J. (2014). The effect of different kick start positions on OMEGA OSB11 blocks on free swimming time to 15m in developmental level swimmers. *Human movement science, 34*, 178-186.

Cossor, J., Slawson, S., Shillabeer, B., Conway, P., & West, A. (2011). *Are land tests a good predictor of swim start performance?* Paper presented at the ISBS-Conference Proceedings Archive.

de Jesus, K., de Jesus, K., Fernandes, R. J., Vilas-Boas, J. P., & Sanders, R. (2014a). The backstroke swimming start: state of the art. *Journal of Human Kinetics*(42), 27-40.

FINA. (2014). Fedération Internationale de Natation. Swimming Rules. http://www.fina.org Retrieved 12 September, 2014

Formicola, D., & Rainoldi, A. (2015). A kinematic analysis to evaluate the start techniques' efficacy in swimming. *Sport Sciences for Health, 11*(1), 57-66.

Gambrel, D. W., Blanke, D., Thigpen, K., & Mellion, M. (1991). Biomechanical comparison of the track start and the modified one-handed track start in competitive swimming: An intervention study. *Journal of Swimming Research, 7*(2), 5-9.

McLean, S. P., Holthe, M. J., Vint, P. F., Beckett, K. D., & Hinrichs, R. N. (2000). Addition of an approach to a swimming relay start. *Journal of applied biomechanics, 16*, 342-355.

Mourão, L., de Jesus, K., Viriato, N., Vilas-Boas, J. P., Monteiro, J., & Vaz, M. A. P. (2015). Design and construction of a 3D force plate prototype for

developing an instrumented swimming start block. *Submitted to Journal of Biomedical Engineering and Informatics*.

Nguyen, C., Bradshaw, E. J., Pease, D., & Wilson, C. (2014). Is starting with the feet out of the water faster in backstroke swimming? *Sports Biomechanics, 13*(2), 154-165.

Roesler, H., Haupenthal, A., Schütz, G. R., & de Souza, P. V. (2006). Dynamometric analysis of the maximum force applied in aquatic human gait at 1.3 m of immersion. *Gait & Posture, 24*(4), 412-417.

Saavedra, J. M., García-Hermoso, A., Escalante, Y., Dominguez, A. M., Arellano, R., & Navarro, F. (2014). Relationship between exchange block time in swim starts and final performance in relay races in international championships. *Journal of Sports Sciences*. doi: 10.1080/02640414.2014.920099

Seifert, L., Vantorre, J., Chollet, D., Toussaint, H. M., & Vilas-Boas, J.-P. (2010). Different profiles of the aerial start phase in front crawl. *The Journal of Strength & Conditioning Research, 24*(2), 507-516.

Slawson, S., Conway, P., Cossor, J., Chakravorti, N., West, A. . (2013). The categorisation of swimming start performance with reference to force generation on the main block and footrest components of the Omega OSB11 start blocks. *Journal of Sports Sciences, 31*, 468 - 478.

Takeda, T., Takagi, H., & Tsubakimoto, S. (2010). *Comparison among three types of relay starts in competitive.* Paper presented at the Biomechanics and Medicine in Swimming XI.

Tor, E., Pease, D. L., & Ball, K. A. (2015). Key parameters of the swimming start and their relationship to start performance. *Journal of Sports Sciences, 33*(13), 1313-1321. doi: 10.1080/02640414.2014.920099

Vantorre, J., Cholet, D., & Seifert, L. (2014). Biomechanical analysis of the swim-start: A review *Journal of Sports Science and Medicine, 13*, 223-231.

Vilas-Boas, J. P., Cruz, J., Sousa, F., Conceicao, F., Fernandes, R., & Carvalho, J. (2003). *Biomechanical analysis of ventral swimming starts: Comparison of the grab start with two track-start techniques.* Paper presented at the Biomechanics and Medicine in Swimming IX, Saint-Étienne, France.

## Chapter 5.2

**Ground Reaction forces produced in track start: Active and Passive force splitting**

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**Abstract**

The implementation of the back plate in the swimming starting blocks improved the popularity of the track start among elite swimmers. However, no research has already determined how swimmers clearly generate the forces to propel themselves out of the block. This study aimed to implement a previous developed tool for horizontal and vertical force assessment based on the swimmers' propulsive and structural forces (passive forces due to dead weight) applied during the block phase of the track start. Two methodological pathways were followed: the swimmers' inertial effect was analytically calculated, and the swimmers' starting action was experimentally assessed, allowing the effective action (active force) to be analysed through both based on the development of a specific mathematical tool. One elite male swimmer with the track start as preferred technique performed three 15 $m$ maximal track start repetitions from an instrumented starting block composed of five triaxial waterproof force plates. The horizontal and vertical passive force contribution to the start performance obtained from the analytical model was subtracted from the experimentally measured force, resulting in the swimmers' active forces. As expected, the swimmers' vertical and horizontal active forces accounted most for the maximum variability of the experimentally observed forces, while the passive forces contribution was almost inexistent. These findings improve understanding about mechanisms of forces generation during the track start and can help swimmers and coaches to improve performance.

Keywords: *dynamometry, external forces, kinematics, modelling, ventral start*

## Introduction

An effective swimming start is an essential part of competitive swimming, particularly in shorter distance events (Cossor et al., 2011), allowing distinguishing between victory and competitive defeat. The start has three phases: the impulse off the starting blocks, the aerial and the underwater phase (Barlow et al., 2014; Saavedra et al., 2014). The movements generated while swimmers are in contact with the starting block should be studied in detail, since the starting phases are considered interdependent (Mason et al., 2007; Vantorre et al., 2014), and coaches often focused in improve swimmers' impulse characteristics (Barlow et al., 2014). A number of different ventral start techniques has been used by swimmers over the years, and particular attention in the literature has been given to two of these: (i) the grab start and (ii) the track start (Barlow et al., 2014; Vantorre et al., 2014). The main difference between the two techniques is the positioning of the feet on the platform. In the grab start, both feet are placed at the front of the platform while the track start is characterized by one foot placed at the front and the other towards the rear of the platform. Researches have provided inconclusive findings to which of these above-referred start techniques is superior (*e.g.,* Blanksby , Nicholson, and Elliott (2002), but a preference for the track start has emerged amongst international level swimmers in recent years (Vint et al., 2009), which is likely to be because the track start reduces the potential for a false start (automatic disqualification) by providing increased stability through a large base of support (R. Breed, Young, & McElroy, 2000).

In 2008, the governing body for swimming (Federation Internationale de Natation Amateur, FINA) amended the rule pertaining to block design and this allowed the

introduction of a new starting block by Omega (OSB11, Switzerland). The OSB 11 is characterized by the addition of an adjustable inclined footrest towards the rear of the platform surface, which is angled at 30º to the platform surface and can be moved to five different positions. The OSB11 allowed the development of the kick-start, a variation of the track start where the rear foot is placed on the inclined footrest rather than the platform surface. Researchers have revealed that this new technique allows a shorter block time (Biel, Fischer, & Kibele, 2010; K. Honda, Sinclair, Mason, & Pease, 2010), higher horizontal take-off velocity (Biel et al., 2010) and faster 5, 7.5 and 15-m times to (Ozeki, Sakurai, Taguchi, & Takise, 2012).

Being the track start force pattern ruled similarly to the grab start after rear foot takes-off instant (Formicola & Rainoldi, 2015; L Mourão et al., 2015), the proper description of ground reaction forces ($\overrightarrow{GRF}(t)$) generated by inertia properties and effective swimmers' action should be examined, as previously done for the grab start (L Mourão et al., 2015). Those authors showed that forces generated during block phase are swimmers' effective actions and inertia properties dependent, which improved start external kinetics understanding and helped coaches to improve start training effectiveness. The segment arrangement with its origin in the front limb (when rear lower limb takes off) combined with initial angular velocity, could lead, once again, to separately assess active $\vec{R}_{Active}(t)$ and passive $\vec{R}_{Passive}(t)$ components, since CM to COP segment and subsequent former grab start considerations could be applied. The minimization of the dispersion of the segments around the sagittal plane ensures preventing spurious momenta that could disturb trajectory heading, roll or both (Bäumker & Heimes, 2001). This requires the following behaviour: non-symmetric limbs minimization

distance to sagittal plane (lower limbs, not symmetrically positioned, are required to lie the most on sagittal plane), free limbs move symmetrically to sagittal plane (upper limbs are symmetrically moved to sagittal plane). These two half body different behaviour requires up to half turn movement to hip, while in contact, in order to maintain the rear limb CM in the vertical of the front limb CM, reversing the movement, while in flight, to lower limb parallelization. Such premises can be supported by the observation: the swimmer flight is zero roll and heading while pitch has the necessary time ratio (or angular velocity) in order to optimize water entry angle (Bäumker & Heimes, 2001). This means that possible roll produced while in contact to block has its counteract while in hip horizontal positioning recovery during flight. At that instant, geometry recovers sagittal symmetry and, as there are non-zero and important cross product inertial components, it turns to be very important that the contact to block force-time history and particularly the total CM-COP segment locus remains in sagittal plane. 'Whip' upward last contact instants rear limb movement (scissor like movement) can be used to produce vertical force in order to lift mostly the CM and also can produce a little bit more of pitch rotation.

The aim of this research is to decompose the most propulsive $\overrightarrow{GRF}(t)$ components (i.e. horizontal and vertical) generated during the track start performed under the current FINA rules (FR 2.7) into active ($\vec{R}_{Active}(t)$) and passive ($\vec{R}_{Passive}(t)$). It is hypothesised that swimmers using the track start would not be able to generate $\vec{R}_{Passive}(t)$ horizontal and vertical components due to a flat angle assumed when swimmers' feet leave the back plate (Tsuyoshi Takeda et al., 2012).

## Method

*Determination of swimmers' inertia matrix*

Starting with a swimmer model (sagittal symmetry not assumed, but with minor cross moment of inertia matrix values), the minimum and maximum values of the nine moment of inertia components calculated around front hallux (in particular $I_{zz}$), defined by the last component of the inertia tensor matrix, were calculated (3D CAD, DS Solidworks, Dassault Systèmes S.A., USA) based on NASA's (NASA, 1978) human body anthropometrical inertial model and are presented in Figure 43. These values were assessed using a model of a rigid articulated body with a mass of 90.48 kg, volume of 90.48 $dm^3$ and surface area of 3.28 $m^2$, compatible with two transient swimmer's inter-segmental realistic body positions assumed during the track start technique: the most grouped position before hands-off (Figure 43, A panel) and the most extended position, just before the take-off (Figure 43, B panel) with CM-COP segment length of 0.720 m and 1.098 m, respectively. The expression "articulated" refers to the reality-based effective transition from the 1st to the 2nd track start positions.

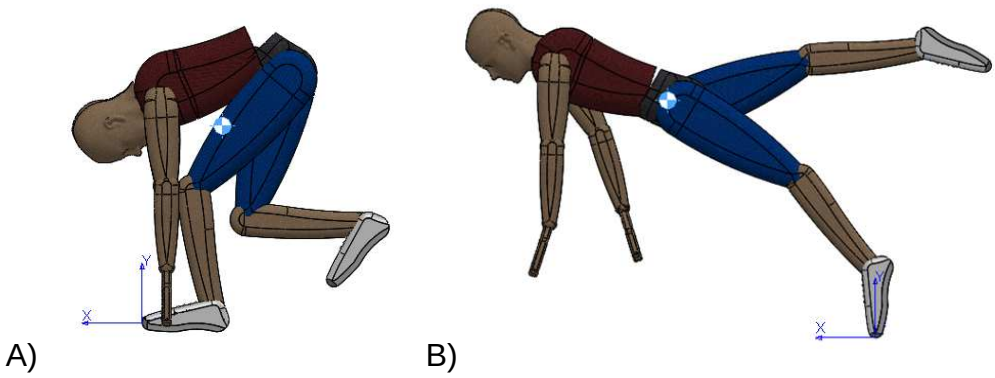


*Figure 43 Representation of two limit of on-contact articulated rigid body compatible with two realistic limit segment distributions of a swimmer, most grouped (A) and most extended (B).*

*Experimental protocol*

A male competitive Olympic swimmer (age: 27 years; height: 1.81 m; body mass: 73 kg), track start performer and a personal best of 114.58 s in 200 m individual medley performance in 25 m pool, representing 95.67 % of the short course Word Record) volunteered to participate. The swimmer was healthy (no serious injury or illness in the last six months) and participated at that time of this study in national and international level competitions with individual medley as his main event. The local Ethics Committee approved the protocol, and all procedures were in accordance with the declaration of Helsinki regarding human subjects research. The swimmer freely provided informed written consent before data collection.

The swimmer answered a questionnaire to assess background information about his best individual performance in ventral events and, following height and body mass measurements, performed a standardized warm up consisting of 600 m swimming (Hardt, Benjanuvatra, & Blanksby, 2009) in a 25 m indoor and heated (27ºC) swimming pool. During the warm up, the swimmer was provided with a familiarization period on the instrumented starting block, which complies FINA facility rules FR 2.7 (FINA, 2009). Swimmer performed three maximal 15-m repetitions of the track start with 2 min rest in-between trials.

The instrumented starting block was composed of five waterproof force plates, according Roesler et al. (2006) design, being two for upper and three for lower limb force assessments, each one with sensitivity of 0.5 N, error < 5% and resonance frequency minimum ~ 200 Hz. Dynamical calibration followed the same steps used by (L Mourão et al., 2015) in the rigid body fall, and revealed homogeneity of results for static calibration. Custom-designed data processing

software (executable file) was created in LabView 2013 (SP1, NI Corp., USA) to acquire, plot and save the strain readings from each force plate (2000 Hz sampling rate). Starting signals were produced conform to FINA rules (SW 4.2) using a starter device (Omega StartTime IV, Swiss Timing Ltd., Switzerland), which was programmed and instrumented to simultaneously generate starting command and export a trigger signal allowing data synchronization with acquired $\overrightarrow{GRF}(t)$ curves and analogue-to-digital converted by a module for strain signals (NI9237, National Instruments Corporation, USA) and respective couple of chassis (CompactDAQ USB-9172, CompactDAQ Eth-9188, NI Corp., USA).

*Data analysis*

Upper and lower limb forces were resolved into horizontal (x) and vertical (y) components accounting for the angle of the block and footrest, as previously done (S. Slawson, Conway, P., Cossor, J., Chakravorti, N., West, A. , 2013). All strain output signals were converted to digital data through an analogue to digital converter via strain gauge input modules NI 9237 connected to chassis NI cDAQ-9172 and NI cDAQ-9188, both developed by the National Instruments Corporation (NI©, USA). Data was processed by matricial algorithms (the transfer function) based on previous static and dynamic calibration. Such new record history was discarded until the moment a single foot is the last force producer (Figure 44).

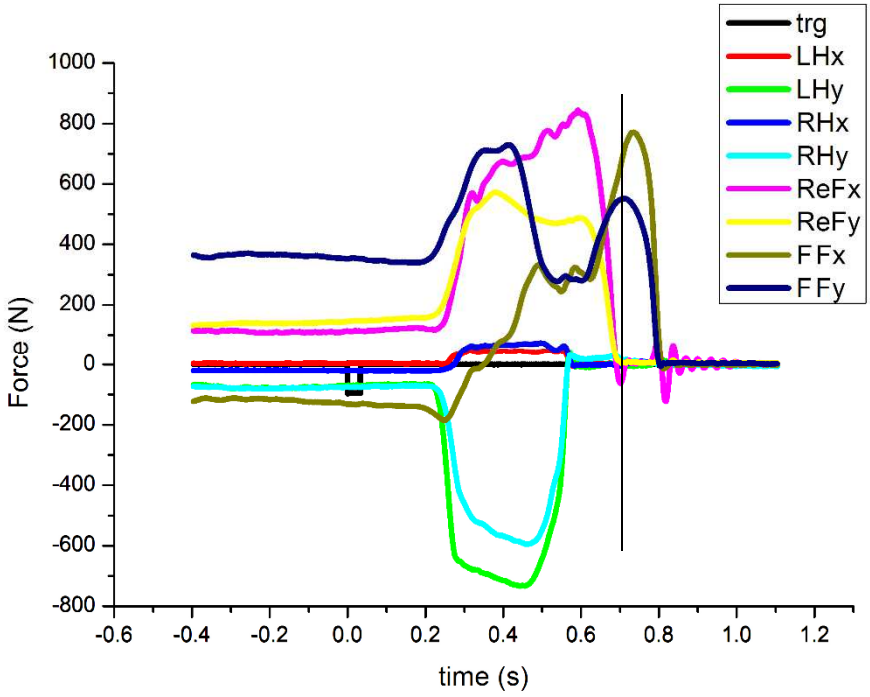


*Figure 44 Representation of forces (trg is the trigger signal; x and y components of LH=left hand; RH=right hand; ReF=rear foot; FF=forward foot) produced on block during track start The vertical continuous line represents the instant of rear limb take-off.*

The algorithm is based on the match of the $\theta = \arctan\left(\frac{F_y}{F_x}\right)$ (where $F_y$ is the vertical force component, $F_y$ is the anterior-posterior force component and $\theta$ is the angle of the CM-COP segment inclination to horizontal) with the one produced by a rigid body with same volumetric mass free fall constrained to be in ground contact by a medio-laterally oriented line (transverse axis) passing by the support hallux. The chosen realistic rigid articulated body mymethises two limit most grouped and extended positions compatible to swimmers' segment spatial distribution (these mymethisations were obtained by video frame segment positioning identification transposed to the rigid articulated body developed in SolidWorks, Dassault Systèmes S.A., France), while in contact to block, suggesting that these would be the limiting maximum and minimum inertia matrix components. The force pattern generated by these model considerations produce the so-called

passive force (L Mourão et al., 2015). The subtraction of this force components to the raw force experimentally registered provide the active force patterns.

**Results and Discussion**

Complete matrix components were calculated and the minimum and maximum inertia matrix component $I_{zz}$ obtained in the respective most grouped and extended articulated rigid body position was used to provide corrections to the model considered in the rigid body fall simulation (Table 5). In the most extended body positions $I_{zz} \gg I_{yz}, I_{xz}$ justifies the non-meaningfulness of differences of $I_{yz}$, $I_{xz}$ values between both rigid articulated body positions. Inertia $I_{zz}$ value almost triplicates from the most contracted to the most extended rigid articulated body positions, which was also observed in grab start (L Mourão et al., 2015). Centre of mass for this position is located at (0.720, 0.829, 0.000) being the $x$, $y$, $z$, coordinates with the International Society of Biomechanics convention, respectively anterior-posterior, vertical and medio-lateral directions. However, in grouped position it is observable a high influence of cross components, other than z component, on account of high asymmetry of this geometry. Rotation around z axis, would no longer be maintained around z axis exclusively, if rotation around hallux was produced. But with the four, or at least, two limb to ground contact, the centre of pressure is between them, being out of algorithm application condition. This suggests more efforts in the future to provide inertia principal axis directions to understand deviations from the natural rotation around front hallux and, particularly, compensation strategies. Indeed, it is necessary to look forward (as is observable) that previous to rear limb lift-off force time evolution should compensate any angular acceleration and angular velocity in the horizontal ($x$)

or vertical ( $y$ ) components, remaining zero, producing a unique final z around hallux component of those physical quantities. This is not unreasonable, as it is not expected any other rotation than the rotation around support hallux (and as expected, in extended position, cross inertia tensor components are very low valued).

*Table 5 Inertia tensors (kg.m2) calculated to hallux rotation point in the two rigid articulated body positions.*

| **Rigid articulated body positions** | **Moment of Inertia matricial components** |
|---|---|
| Most grouped | $\begin{bmatrix} I_{xx} & I_{xy} & I_{xz} \\ I_{yx} & I_{yy} & I_{yz} \\ I_{zx} & I_{zy} & I_{zz} \end{bmatrix} = \begin{bmatrix} 45.967783 & 4.361029 & -2.020117 \\ 4.361029 & 11.545209 & -16.082234 \\ -2.020117 & -16.082234 & 54.483311 \end{bmatrix}$ |
| Most extended | $\begin{bmatrix} I_{xx} & I_{xy} & I_{xz} \\ I_{yx} & I_{yy} & I_{yz} \\ I_{zx} & I_{zy} & I_{zz} \end{bmatrix} = \begin{bmatrix} 66.563057 & 56.901685 & -0.197377 \\ 56.901685 & 62.227914 & 0.503243 \\ -0.197377 & 0.503243 & 126.70699 \end{bmatrix}$ |

Figure 45 represents the theta angle profile, which was reducing from the rear foot take-off until the front lower limb take-off with magnitude < 40º at the first instants. In a previous study conducted for splitting $\vec{R}_{Active}(t)$ and passive $\vec{R}_{Passive}(t)$ during the grab start technique (L Mourão et al., 2015), it was observed that swimmers generated an angle of ~ 90º at the auditory signal and ~ 45º during the take-off. Therefore, in the grab start, swimmers were able to apply horizontal and vertical reaction forces due to inertia effects in a considerable percentage of body weight from the auditory signal until the hands-off, being the effective horizontal and vertical force contribution notorious from then on (L Mourão et al., 2015). In

opposition, in the track start, the contribution of $\vec{R}_{Passive}(t)$ was depicted almost inexistent due to the small theta angle registered (force angle to horizontal) and a noticeable horizontal force peak just before the take-off. Considering the new track start with the back plate used in ventral swimming events, it was observed that swimmers increased the horizontal reaction force and applied a greater horizontal take-off velocity (K. E. Honda et al., 2012). In fact, it was already assumed that sprint starts for track events in athletics use a starting block that tends to generate greater horizontal velocity (Slawinski et al., 2012). The back plate is generally used as the standard model in international competitions and can be fixed at several different locations on the starting block. On the conventional starting platform with no back plate and an inclination of 10º from the surface of the starting block, a certain amount of vertical force is required to prevent the rear foot from slipping backward (Tsuyoshi Takeda et al., 2012). The back plate on the new starting block increases the inclination of the rear foot, thus, lifting the heel, which deflects the force applied by the rear lower limb perpendicular to the surface of the back plate towards the horizontal direction (Formicola & Rainoldi, 2015; Tsuyoshi Takeda et al., 2012). Therefore, the addition of the back plate to the starting block was suggested to increase the horizontal reaction force on the rear foot (which must not slip) (Tsuyoshi Takeda et al., 2012).

In the light of the above-mentioned observations, it was expectable that swimmers would not generate noticeable vertical force component and would adopt a flat take-off angle. The horizontal and vertical force curves obtained in the current study were similar to the example presented by S. Slawson, Conway, P., Cossor, J., Chakravorti, N., West, A. (2013) in terms of profile and magnitude.

Those authors hypothesized that the footrest (backplate) is capable of improving staring performance, which should be represented in the force generated on the main platform. They observed that higher than average horizontal and vertical peak forces from the main block can be understood, as in the most cases these peaks occur in this final push off phase. Indeed, authors have corroborated this idea, recommending coaches to enhance the horizontal force component of propulsive force produced during the block phase (Formicola & Rainoldi, 2015).

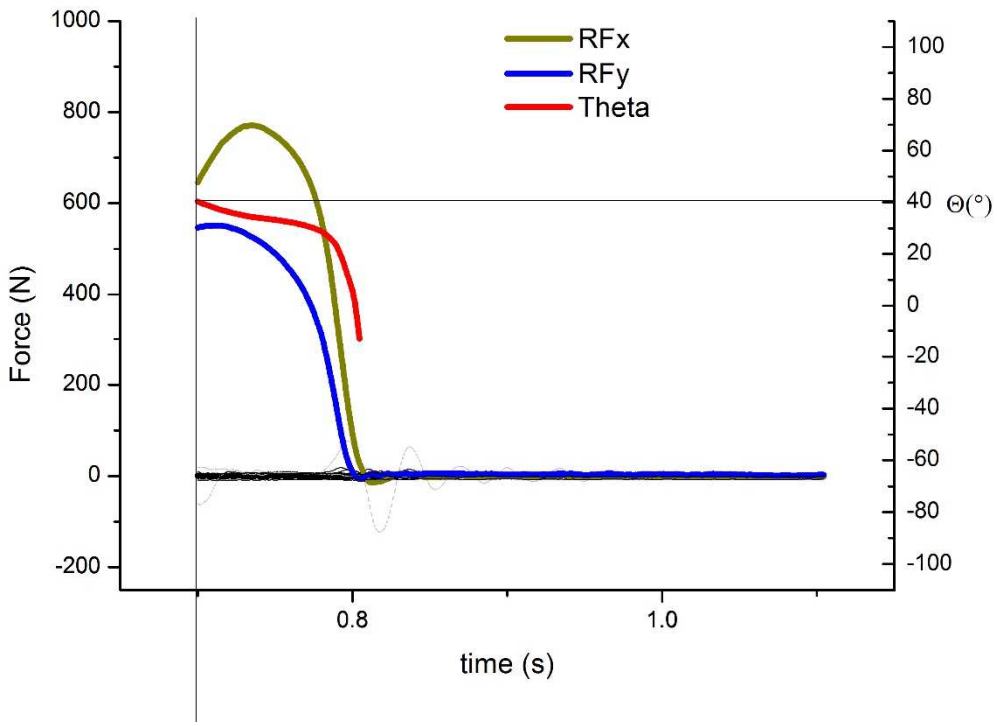


*Figure 45 Zoom on the forces represented (x and y components of right foot, Theta=Force angle to horizontal) produced on block during track start.*

The new track or kick start has been shown to be the faster start off the start platform when compared to the track or bunch start (Biel et al., 2010), and regardless of the CM assumed variant (front or rear) swimmers would present

similar $\vec{R}_{Passive}(t)$ contribution. Competition analysis studies verified that the new platforms provided swimmers with shorter block times than swimmers performing the traditional track start (Garcia-Hermoso et al., 2013). It may be assumed that shorter block time is indicative of better performance; however, this is not necessarily true (Barlow et al., 2014). Based on the current data, it could be recommended for coaches to emphasize the block time to generate greater horizontal peak forces and impulses, since swimmers propulsion is essentially dependent upon effective actions. Moreover, coaches should attempt to take the most out of resistance-training programs to enhance swimmers capability to generate greater horizontal peak force, as previously recommended by R. V. Breed and Young (2003).

**Conclusion**

It was observed no passive force produced during the track start performed with the new backplate (kick start), once at the considered instant of algorithm application, the force angle to horizontal is below 40º (the limit angle preconized to passive force remain). It is necessary to consider that the swimmer establishes the backplate position at will, meaning that this choice is determined by the most closed rear limb lift-off so that front hallux (COP after rear limb lift off) to CM segment introduces no passive load (allowing the total force produced thereon as purely active, and so, totally propulsive). If, by some reason, the swimmer stops propulsion, the take-off is guaranteed anyway and contact to block is lost in fact.

## References


Barlow, H., Halaki, M., Stuelcken, M., Greene, A., & Sinclair, P. J. (2014). The effect of different kick start positions on OMEGA OSB11 blocks on free swimming time to 15m in developmental level swimmers. *Human movement science, 34*, 178-186.

Bäumker, M., & Heimes, F. (2001). *New calibration and computing method for direct georeferencing of image and scanner data using the position and angular data of an hybrid inertial navigation system.* Paper presented at the OEEPE Workshop, Integrated Sensor Orientation.

Biel, K., Fischer, S., & Kibele, A. (2010). Kinematic analysis of take-off performance in elite swimmers: New OSB11 versus traditional starting block. *Biomechanics and Medicine in Swimming XI*.

Blanksby , B., Nicholson, L., & Elliott, B. (2002). Biomechanical analysis of the grab, track and handle swimming starts: An intervention study. *Sports Biomechanics, 1*(1), 11-24.

Breed, R., Young, W., & McElroy, G. (2000). The effect of a resistance-training program on the grab, swing, and track starts in swimming. 2000 Pre-Olympic Congress in Sports Medicine and Physical Education: International Congress on Sport Science. Brisbane, Australia.

Breed, R. V., & Young, W. B. (2003). The effect of a resistance training programme on the grab, track and swing starts in swimming. *Journal of Sports Sciences, 21*(3), 213-220.

Cossor, J., Slawson, S., Shillabeer, B., Conway, P., & West, A. (2011). *Are land tests a good predictor of swim start performance?* Paper presented at the ISBS-Conference Proceedings Archive.

FINA. (2009). Fedération Internationale de Natation. Facilities Rules. http://www.fina.org Retrieved 12 September, 2014

Formicola, D., & Rainoldi, A. (2015). A kinematic analysis to evaluate the start techniques' efficacy in swimming. *Sport Sciences for Health, 11*(1), 57-66.

Garcia-Hermoso, A., Escalante, Y., Arellano, R., Navarro, F., Domínguez, A. M., & Saavedra, J. M. (2013). Relationship between final performance and block times with the traditional and the new starting platforms with a back plate in international swimming championship 50-m and 100-m freestyle events. *Journal of sports science & medicine, 12*(4), 698-706.

Hardt, J., Benjanuvatra, N., & Blanksby, B. (2009). Do footedness and strength asymmetry relate to the dominant stance in swimming track start? *Journal of Sports Sciences, 27*(11), 1221-1227.

Honda, K., Sinclair, P., Mason, B., & Pease, D. (2010). *A biomechanical comparison of elite swimmers start performance using the traditional track start and the new kick start.* Paper presented at the XIth International Symposium for Biomechanics and Medicine in Swimming.

Honda, K. E., Sinclair, P. J., Mason, B. R., & Pease, D. L. (2012). *The effect of starting position on elite swim start performance using an angled kick plate.* Paper presented at the International Society of Biomechanics in Sports.

Mason, B., Alcock, A., & Fowlie, J. (2007). *A kinetic analysis and recommendations for elite swimmers performing the sprint start.* Paper presented at the ISBS-Conference Proceedings Archive.

Mourão, L., de Jesus, K., Viriato, N., Vilas-Boas, J. P., Monteiro, J., & Vaz, M. A. P. (2015). Design and construction of a 3D force plate prototype for

developing an instrumented swimming start block. *Submitted to Journal of Biomedical Engineering and Informatics*.

NASA. (1978). *Anthropometric source book.* (Vol. Volume I: Anthropometry for designers. ): Ohio: Yellow Springs.

Ozeki, K., Sakurai, S., Taguchi, M., & Takise, S. (2012). *Kicking the back plate of the starting block improves start phase performance in competitive swimming.* Paper presented at the ISBS-Conference Proceedings Archive.

Roesler, H., Haupenthal, A., Schütz, G. R., & de Souza, P. V. (2006). Dynamometric analysis of the maximum force applied in aquatic human gait at 1.3 m of immersion. *Gait & Posture, 24*(4), 412-417.

Saavedra, J. M., García-Hermoso, A., Escalante, Y., Dominguez, A. M., Arellano, R., & Navarro, F. (2014). Relationship between exchange block time in swim starts and final performance in relay races in international championships. *Journal of Sports Sciences*. doi: 10.1080/02640414.2014.920099

Slawinski, J., Dumas, R., Cheze, L., Ontanon, G., Miller, C., & Mazure-Bonnefoy, A. (2012). 3D kinematic of bunched, medium and elongated sprint start. *International Journal of Sports and Medicine, 33*(7), 555-560.

Slawson, S., Conway, P., Cossor, J., Chakravorti, N., West, A. . (2013). The categorisation of swimming start performance with reference to force generation on the main block and footrest components of the Omega OSB11 start blocks. *Journal of Sports Sciences, 31*, 468 - 478.

Takeda, T., Takagi, H., & Tsubakimoto, S. (2012). Effect of inclination and position of new swimming starting block's back plate on track-start performance. *Sports Biomechanics, 11*(3), 370-381.

Vantorre, J., Cholet, D., & Seifert, L. (2014). Biomechanical analysis of the swim-start: A review *Journal of Sports Science and Medicine, 13*, 223-231.

Vint, P., Mclean, S., Hinrichs, R., Riewald, S., & Mason, R. (2009). *Effects of handle and block configuration on swim start performance.* Paper presented at the ISBS-Conference Proceedings Archive (XXVII).

# Chapter 6.

## Synopsis of findings and conclusions

This chapter is a brief synopsis of the findings of this thesis, presented in the earlier Chapters and supporting the following General Conclusions.

Introduction provided the rational and an overview of this thesis. A brief description of the used and described ventral start techniques is synthetically presented.

Chapter 2 gave a glimpse of the state-of-the-art on kinetic measurement adapted to swimming starts. It is also presented some of the features that should be included in a new dynamometric device, like individual four-limb propulsive contribution.

Chapter 3 targeted the implementation of a dynamometric device in order to assess individualized four-limb reaction force. Such task, started by a very initial stage load cell (Chapter 3.1) where some of the insight was amplified and most of the software strategies and presentation of results were developed. Chapter 3.2, evolved around replication of a core load cell in judicious placement/dimensions in order to cover the overall swimmer's limb contact to ground, or spatial layout. During the development, it was evident the need to consider time layout to accommodate the various families of events to be recorded, from the application to swimming point of view, as well as, on the technical side, development of hardware adaptive to synchronism behaviour.

Chapter 4 presented a tool developed to split Active from Passive force, in grab start, exhibiting some consequences and also some questions about what is voluntary force and what is the fall contribution. One of the main consequences is the belief that part of the jump results from a rotational form of falling, of a limit angle at which contact is maintained exclusively by active force production.

Chapter 5 presented application mainly of the Chapter 3 and 4 concepts to the relay changeovers and to track start: sub chapter 5.1 and 5.2, respectively. Indeed Chapter 5.1 applies to on motion changeovers evidencing that the dynamometric device prototype allow such particularly echo-general measurement. Out of it, it was possible to show that step moving starts, compared to conventional and track starts, are characterized by lower levels of force application, particularly from the moving limb, both in anterior-posterior and vertical directions. Another result, less evident, seems to be the non-immediate weight relief to the movable limb when it contacts to the platform. This way even when both limbs are in contact is the fixed one which has the major contribution. This is evidenced by on frontal platforms vertical components of last ground reaction forces applied right and left respectively in the one step and two step changeover techniques. Track start was presented as a qualitative comparison term. This can be easily performed by the system because, although front reaction forces are measured individually, they can be added together. In Chapter 5.2 track start is again picked up but this time with the objective of splitting the active from passive force where the algorithm is applicable. What has been shown is that swimmer chooses the backplate positioning and, doing so, rear limb propulsion is maintained precisely until centre of pressure to centre of mass segment declines below the limit angle to passive force. Such reasoning means that fatally take-off would be exhibited even without front limb force (all of it active) exerted.

The purpose of this thesis was to develop new conceptual and instrumental solutions for better understanding, evaluating and advice the training process of swimming ventral starts in truly ecological conditions with a full dynamometric picture. Secondly, it was also aimed to apply these new contributions to the changeover starting techniques, which have rarely been investigated. To fulfil these objectives, a novel dynamometric device able to ecologically measure the

four limbs 3D6DoF kinetics of swimmers during ventral starts was developed (patent pending). Also an analytical model was proposed to decompose swimmer's kinetics into "inertial" and "active" forces during ventral starts. Both contributions were fully innovative and unique.

This way, the implementation of the force-by-limb distinguishing purpose of the dynamometric device, as was observed in Chapter 2, was urged while adapted for the start techniques (ventral mainly, extended to backstroke and including relay changeovers).

In Chapter 3, a dynamometric station was implemented to provide wide use in various techniques to be studied and/or to be used in training evaluation and coaching advice. First steps toward this achievement allowed also the development of a "didactic" force plate for extensometric explorations.

Simultaneously, in Chapter 4 a tool was developed to split Active from Passive force components during ventral swimming starts, exhibiting the merits and also some questions about what is voluntary force or not. Indeed even without propulsive "active" force generated by the swimmer's will (i. e., rigid body behaviour) some propulsion still remains and take-off eventually happens at about ~40º to horizontal.

Chapter 5 applies both the Chapter 3 and 4 innovations and shows that it is possible to analyse the relay changeover starting technics kinetics, revealing features that were not known, to date, as relevant weaknesses of force production during step in-motion starts, particularly concerning the stepping limb. Sub-complementing Chapter 4 for the currently mostly used ventral starting technique in swimming events, Chapter 5.2 is a force decomposition of the on block last contact forces during the track start, performed with the newly approved backplate (or kick start). It was evidenced the effect of the backplate on the production of horizontal forces and the "active" nature of the main propelling forces used in this starting technique.

Whichever situation was described in the Chapter 5, concepts of Chapter 3 and 4 still applies, turning the overall toolbox powerful, even though not capable to substitute the coach. Presently the previews characterization needs coach eyes

to identify the quality of start technique so that it is possible to map these to force patterns being this information crucial to optimize the start technique.

These challenging questions should be object of posterior works, perhaps using the dynamometric device together with kinematics and electromyography.

Beyond the swimmer's starting force pattern quality control, future work is already in perspective. Without changing the spatial layout, it is important to continually improve the load cell core of the proposed and dynamometrical device. Some of the mechanical strategies are already identified as the next step to implement. Surely, water resistance and chloride resistance, are urgent improvements. The electronic hardware with some changes can also address positioning of the backplate, allowing simultaneous recording of such variable. Software is a various environment toolbox on account of the peculiarities of any prototype of a dimension such as the dynamometric device exhibits: origin, matlab and labview were used with different purposes. Next step should be the higher labview integration of the various modules to allow the use of the very good graphical interface in order to identify COP and GRF produced by each of the swimmer´s limbs. Calibration is a very cumbersome work and use of speedy procedures is desirable. One way is, again, to use Chapter 4 results as dynamical fall with contact point results in a known force pattern and fast measurement. However, this operation is better to be used with some care as calibration by the distinct methods provide transfer functions that can be different. One last management forecast should be the investment on automate report (today already received in any tablet or similar) in order to observe fast results (perhaps it will be necessary to downsize graphs and images) but it is better to have an immediate although with less resolution force pattern directly delivered to the swimmer's coach. Moreover, the integration in this software of the decomposition algorithm proposed in Chapter 4.

Finally another system improvement which is forecast is the development of a neuronal algorithm which, using the signals recorded from an event, can identify the type of start technique and rank its performance.

## References


Arellano, R., Llana, S., Tella, V., Morales, E., & Mercade, J. (2008). *A comparison CMJ, simulated and swimming grab-start force recordings and their relationships with the start performance.* Paper presented at the ISBS-Conference Proceedings Archive.

Barlow, H., Halaki, M., Stuelcken, M., Greene, A., & Sinclair, P. J. (2014). The effect of different kick start positions on OMEGA OSB11 blocks on free swimming time to 15m in developmental level swimmers. *Human movement science, 34*, 178-186.

Bäumker, M., & Heimes, F. (2001). *New calibration and computing method for direct georeferencing of image and scanner data using the position and angular data of an hybrid inertial navigation system.* Paper presented at the OEEPE Workshop, Integrated Sensor Orientation.

Benjanuvatra, N., LytUe, A., Blanksby, B., & Larkin, D. (2004). Force development profile of the lower limbs in the grab and track start in swimming. *Analysis, 14606*(151), 94.

Biel, K., Fischer, S., & Kibele, A. (2010). Kinematic analysis of take-off performance in elite swimmers: New OSB11 versus traditional starting block. *Biomechanics and Medicine in Swimming XI*.

Blanksby , B., Nicholson, L., & Elliott, B. (2002). Biomechanical analysis of the grab, track and handle swimming starts: An intervention study. *Sports Biomechanics, 1*(1), 11-24.

Bobbert, M. F., & Schamhardt, H. C. (1990). Accuracy of determining the point of force application with piezoelectric force plates. *Journal of Biomechanics, 23*(7), 705-710.

Bracci, J. M., Reinhorn, A. M., & Mander, J. B. (1992). Seismic resistance of reinforced concrete frame structures designed only for gravity loads: Part I-Design and properties of a one-third scale model structure. *Technical Rep. No. NCEER-92, 27*.

Breed, R., Young, W., & McElroy, G. (2000). The effect of a resistance-training program on the grab, swing, and track starts in swimming. 2000 Pre-Olympic Congress in Sports Medicine and Physical Education: International Congress on Sport Science. Brisbane, Australia.

Breed, R. V., & Young, W. B. (2003). The effect of a resistance training programme on the grab, track and swing starts in swimming. *Journal of Sports Sciences, 21*(3), 213-220.

Browne, J., & O'Hare, N. (2000). A quality control procedure for force platforms. *Physiological measurement, 21*(4), 515.

Cappello, A., Bagalà, F., Cedraro, A., & Chiari, L. (2011). Non-linear re-calibration of force platforms. *Gait & Posture, 33*(4), 724-726.

Cavanagh, P., Palmgren, J., & Kerr, B. (1975). A device to measure forces at the hands during the grab start. *Swimming II, International series of sport science*, 43-50.

Collins, S. H., Adamczyk, P. G., Ferris, D. P., & Kuo, A. D. (2009). A simple method for calibrating force plates and force treadmills using an instrumented pole. *Gait & Posture, 29*(1), 59-64.

Cossor, J., Slawson, S., Shillabeer, B., Conway, P., & West, A. (2011). *Are land tests a good predictor of swim start performance?* Paper presented at the ISBS-Conference Proceedings Archive.

de Jesus, K., de Jesus, K., Fernandes, R. J., Vilas-Boas, J. P., & Sanders, R. (2014a). The backstroke swimming start: state of the art. *Journal of Human Kinetics*(42), 27-40.

de Jesus, K., de Jesus, K., Figueiredo, P., Gonçalves, P., Pereira, S. M., Vilas-Boas, J. P., & Fernandes, R. J. (2013). Backstroke start kinematic and kinetic changes due to different feet positioning. *Journal of Sports Sciences, 31*(15), 1665-1675.

de Jesus, K., de Jesus, K., Figueiredo, P., Gonçalves, P., Pereira, S. M., Vilas-Boas, J.P., Fernandes, R.J. (2011). Biomechanical analysis of backstroke swimming starts. *Int. J. of Sports Med., 32*, 546-551.

Elipot, M., Hellard, P., Taïar, R., Boissière, E., Rey, J., Lecat, S., & Houel, N. (2009). Analysis of swimmers' velocity during the underwater gliding motion following grab start. *Journal of Biomechanics, 42*(9), 1367-1370.

Elliott, G. M., Sinclair, H. . (1971). The influence of block angle on swimming sprint starts. *In L. Lewillie, J.P. Clarys (Eds.), Biomechanics*, 183-189.

Esser, S. M., Vlietstra, N. J., Farley, D. P., Medicherla, A., Sokn, S. A., Collins, C. J., . . . Zinn, M. R. (2013). An extramedullary three degree of freedom limb deformity correction device for pediatric applications. *J. Med. Device*, 1-26.

FINA. (2009). Fedération Internationale de Natation. Facilities Rules. http://www.fina.org Retrieved 12 September, 2014

FINA. (2014). Fedération Internationale de Natation. Swimming Rules. http://www.fina.org Retrieved 12 September, 2014

Formicola, D., & Rainoldi, A. (2015). A kinematic analysis to evaluate the start techniques' efficacy in swimming. *Sport Sciences for Health, 11*(1), 57-66.

Galbraith, H., Scurr, J., Hencken, C., Wood, L., & Graham-Smith, P. (2008). Biomechanical comparison of the track start and the modified one-handed track start in competitive swimming: An intervention study. *Journal of applied biomechanics, 24*(4), 307-315.

Gambrel, D. W., Blanke, D., Thigpen, K., & Mellion, M. (1991). Biomechanical comparison of the track start and the modified one-handed track start in competitive swimming: An intervention study. *Journal of Swimming Research, 7*(2), 5-9.

Garcia-Hermoso, A., Escalante, Y., Arellano, R., Navarro, F., Domínguez, A. M., & Saavedra, J. M. (2013). Relationship between final performance and block times with the traditional and the new starting platforms with a back plate in international swimming championship 50-m and 100-m freestyle events. *Journal of sports science & medicine, 12*(4), 698-706.

Guimaraes, A. C. S., & Hay, J. G. (1985). A mechanical analysis of the grab starting technique in swimming. *International Journal of sport biomechanics, 1*(1), 25-35.

Hardt, J., Benjanuvatra, N., & Blanksby, B. (2009). Do footedness and strength asymmetry relate to the dominant stance in swimming track start? *Journal of Sports Sciences, 27*(11), 1221-1227.

Hay, J., Guimaraes, A., & Grimston, S. (1983). A quantitative look at swimming biomechanics. *Swimming technique, 20*(2), 11-17.

Hohmann, A., Fehr, U., Kirsten, R., & Krueger, T. (2008). Biomechanical analysis of the backstroke start technique in swimming. (2), 28-33.

Holfelder, B., Brown, N., & Bubeck, D. (2013). The influence of sex, stroke and distance on the lactate characteristics in high performance swimming. *PloS One*(8). doi: 10.1371/journal.pone.0077185

Honda, K., Sinclair, P., Mason, B., & Pease, D. (2010). *A biomechanical comparison of elite swimmers start performance using the traditional track start and the new kick start.* Paper presented at the XIth International Symposium for Biomechanics and Medicine in Swimming.

Honda, K. E., Sinclair, P. J., Mason, B. R., & Pease, D. L. (2012). *The effect of starting position on elite swim start performance using an angled kick plate.* Paper presented at the International Society of Biomechanics in Sports.

Kibele, A., Siekmann, T., & Ungerechts, B. (2008). *A biomechanical evaluation of dive start performance in swimming-force development characteristics and angular momentum,.* Paper presented at the ISBS-Conference Proceedings Archive.

Kilduff, L. P., Cunningham, D. J., Owen, N. J., West, D. J., Bracken, R. M., & Cook, C. J. (2011). Effect of postactivation potentiation on swimming starts in international sprint swimmers. *The Journal of Strength & Conditioning Research, 25*(9), 2418-2423.

Krüger, T., Wick, D., Hohmann, A., El-Bahrawi, M., & Koth, A. (2003). *Biomechanics of the grab and track start technique.* Paper presented at the Proceeding of the IX International Symposium on Biomechanics and Medicine in Swimming.—France: University of Saint-Etienne.

Lyttle, A., & Benjanuvatra, N. (2005). Start Right–A Biomechanical Review of Dive Start Performance. *Zugriff am, 15*.

Lywood, D., Adams, D., Van Eyken, A., & Macpherson, J. (1987). Small, triaxial force plate. *Medical and Biological Engineering and Computing, 25*(6), 698-701.

Maglischo, E. W. (2003). *Swimming fastest* (Champaign Ill ed.): Human Kinetics.

Mason, B., Alcock, A., & Fowlie, J. (2007). *A kinetic analysis and recommendations for elite swimmers performing the sprint start.* Paper presented at the ISBS-Conference Proceedings Archive.

Mason, B., Mackintosh, C., & Pease, D. (2012). *The development of an analysis system to assist in the correction of inefficiencies in starts and turns for elite competitive swimming.* Paper presented at the ISBS-Conference Proceedings Archive, Melbourne: Australian Catholic University.

McLean, S. P., Holthe, M. J., Vint, P. F., Beckett, K. D., & Hinrichs, R. N. (2000). Addition of an approach to a swimming relay start. *Journal of applied biomechanics, 16*, 342-355.

Mourão, L., de Jesus, K., de Jesus, K., Fernandes, R. J., Vaz, M. A., & Vilas-Boas, J. P. (2014). External kinetics in individual and relay swimming starts: a review. *XII International Symposium for Biomechanics and Medicine in Swimming*, 179-184.

Mourão, L., de Jesus, K., Viriato, N., Vilas-Boas, J. P., Monteiro, J., & Vaz, M. A. P. (2015). Design and construction of a 3D force plate prototype for developing an instrumented swimming start block. *Submitted to Journal of Biomedical Engineering and Informatics*.

Naemi, R., Arshi, A., Ahadian, A., & Barjasteh, B. (2001). *3d kinematic and kinetic analyses of two methods for grab start technique.* Paper presented at the ISBS-Conference Proceedings Archive (XXIX).

NASA. (1978). *Anthropometric source book.* (Vol. Volume I: Anthropometry for designers. ): Ohio: Yellow Springs.

Nguyen, C., Bradshaw, E. J., Pease, D., & Wilson, C. (2014). Is starting with the feet out of the water faster in backstroke swimming? *Sports Biomechanics, 13*(2), 154-165.

O'Driscoll, C., Stanley, W., & Little, E. (2013). An Examination of Various Methods of Minimising Strain Gradients in 3D Embedded Strain Gauge Analysis. *Strain, 49*(6), 507-520.

Ozeki, K., Sakurai, S., Taguchi, M., & Takise, S. (2012). *Kicking the back plate of the starting block improves start phase performance in competitive swimming.* Paper presented at the ISBS-Conference Proceedings Archive.

Pinto, A. M., & Lopez-Amo, M. (2012). Photonic crystal fibers for sensing applications. *Journal of Sensors, 2012*, 1-22.

Portaria nº 949-A/2006 de 11 de Setembro. Regras Técnicas das Instalações Eléctricas de Baixa Tensão. (2006).

Preatoni, E., Hamill, J., Harrison, A. J., Hayes, K., Van Emmerik, R. E., Wilson, C., & Rodano, R. (2013). Movement variability and skills monitoring in sports. *Sports Biomechanics, 12*(2), 69-92.

Roesler, H., Haupenthal, A., Schütz, G. R., & de Souza, P. V. (2006). Dynamometric analysis of the maximum force applied in aquatic human gait at 1.3 m of immersion. *Gait & Posture, 24*(4), 412-417.

Roriz, P., Carvalho, L., Frazão, O., Santos, J. L., & Simões, J. A. (2014). From conventional sensors to fibre optic sensors for strain and force

measurements in biomechanics applications: A review. *Journal of Biomechanics, 47*(6), 1251-1261.

Saavedra, J. M., García-Hermoso, A., Escalante, Y., Dominguez, A. M., Arellano, R., & Navarro, F. (2014). Relationship between exchange block time in swim starts and final performance in relay races in international championships. *Journal of Sports Sciences*. doi: 10.1080/02640414.2014.920099

Seifert, L., Vantorre, J., Chollet, D., Toussaint, H. M., & Vilas-Boas, J.-P. (2010). Different profiles of the aerial start phase in front crawl. *The Journal of Strength & Conditioning Research, 24*(2), 507-516.

Shierman, G. (1978). Stability in competitive swimming starts. *Swimming Techniques, 14*, 117-118.

Slawinski, J., Dumas, R., Cheze, L., Ontanon, G., Miller, C., & Mazure-Bonnefoy, A. (2012). 3D kinematic of bunched, medium and elongated sprint start. *International Journal of Sports and Medicine, 33*(7), 555-560.

Slawson, S., Conway, P., Cossor, J., Chakravorti, N., West, A. . (2013). The categorisation of swimming start performance with reference to force generation on the main block and footrest components of the Omega OSB11 start blocks. *Journal of Sports Sciences, 31*, 468 - 478.

Slawson, S. E., Conway, P. P., Cossor, J., Chakravorti, N., Le-Sage, T., & West, A. A. (2011). The effect of start block configuration and swimmer kinematics on starting performance in elite swimmers using the Omega OSB11 block. *Procedia Engineering, 13*, 141-147.

Stevenson, J. R., & Morehouse, C. A. (1979). *Influence of Starting-Block Angle on the Grab Start in Competitive Swimming.* Paper presented at the Swimming III.

Takeda, T., Takagi, H., & Tsubakimoto, S. (2010). *Comparison among three types of relay starts in competitive.* Paper presented at the Biomechanics and Medicine in Swimming XI.

Takeda, T., Takagi, H., & Tsubakimoto, S. (2012). Effect of inclination and position of new swimming starting block's back plate on track-start performance. *Sports Biomechanics, 11*(3), 370-381.

Tor, E., Pease, D. L., & Ball, K. A. (2015). Key parameters of the swimming start and their relationship to start performance. *Journal of Sports Sciences, 33*(13), 1313-1321. doi: 10.1080/02640414.2014.920099

Vantorre, J., Cholet, D., & Seifert, L. (2014). Biomechanical analysis of the swim-start: A review *Journal of Sports Science and Medicine, 13*, 223-231.

Vantorre, J., Seifert, L., Fernandes, R., Vilas-Boas, J., & Chollet, D. (2010a). Kinematical profiling of the front crawl start. *International journal of sports medicine, 31*(01), 16-21.

Vantorre, J., Seifert, L., Fernandes, R., Vilas Boas, J., & Chollet, D. (2010b). Comparison of grab start between elite and trained swimmers. *International journal of sports medicine, 31*(12), 887-893.

Vilas-Boas, J. P., Cruz, J., Sousa, F., Conceicao, F., Fernandes, R., & Carvalho, J. (2003). *Biomechanical analysis of ventral swimming starts: Comparison of the grab start with two track-start techniques.* Paper presented at the Biomechanics and Medicine in Swimming IX, Saint-Étienne, France.

Vilas-Boas, J. P., Cruz, M. J., Sousa, F., Conceição, F., & Carvalho, M. J. (2000). *Integrated kinematic and dynamic analysis of two track-start techniques.* Paper presented at the ISBS-Conference Proceedings Archive (XVIII).

Vint, P., Mclean, S., Hinrichs, R., Riewald, S., & Mason, R. (2009). *Effects of handle and block configuration on swim start performance.* Paper presented at the ISBS-Conference Proceedings Archive (XXVII).

Walicka-Cupryś, K., Przygoda, Ł., Czenczek, E., Truszczyńska, A., Drzał-Grabiec, J., Zbigniew, T., & Tarnowski, A. (2014). Balance assessment in hearing-impaired children. *Research in developmental disabilities, 35*(11), 2728-2734.

Walsh, M. S., Ford, K. R., Bangen, K. J., Myer, G. D., & Hewett, T. E. (2006). The validation of a portable force plate for measuring force-time data during jumping and landing tasks. *The Journal of Strength & Conditioning Research, 20*(4), 730-734.

Wu, G., Siegler, S., Allard, P., Kirtley, C., Leardini, A., Rosenbaum, D., . . . Stokes, I. (2002). ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion-Part I: Ankle, hip, and spine. *Journal of Biomechanics, 35*, 543-548.

Zatsiorsky, V., Bulgakova, N. Z., & Chaplinsky, N. (1979). *Biomechanical analysis of starting techniques in swimming*.