INTERNATIONAL DOCTORAL THESIS AND COTUTELLE

Doctoral Programme in Biomedicine	*Doctoral Programme of Kinesiology*
Department of Physical Education and Sport	*Department of Kinesiology*
Faculty of Sport Sciences	*Faculty of Sport*
University of Granada	*University of Ljubljana*

EFFECT OF ASCENT TO A MODERATE ALTITUDE ON MUSCLE PERFORMANCE IN DIFFERENT STRENGTH MANIFESTATIONS

SUPERVISORS:

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To my parents, family, and Alba

International Doctoral Thesis and Cotutelle

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Que la Tesis Doctoral titulada “Effect of ascent to a moderate altitude on muscle performance in different strength manifestations” que presenta D. Amador García Ramos al superior juicio del Tribunal que designe la Universidad de Granada, ha sido realizada bajo mi dirección durante los años 2012-2016, siendo expresión de la capacidad técnica e interpretativa de su autor en condiciones tan aventajadas que le hacen merecedor del Título de Doctor por la Universidad de Granada y Universidad de Liubliana, siempre y cuando así lo considere el citado Tribunal.

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CERTIFICA:

Que la Tesis Doctoral titulada "Effect of ascent to a moderate altitude on muscle performance in different strength manifestations" que presenta D. Amador García Ramos al superior juicio del Tribunal que designe la Universidad de Granada, ha sido realizada bajo mi dirección durante los años 2012-2016, siendo expresión de la capacidad técnica e interpretativa de su autor en condiciones tan aventajadas que le hacen merecedor del Título de Doctor por la Universidad de Granada y Universidad de Liubliana, siempre y cuando así lo considere el citado Tribunal.

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En Granada, 31 de Mayo de 2016

El doctorando D. AMADOR GARCÍA RAMOS y los directores de la tesis Dña. BELÉN FERICHE FERNÁNDEZ-CASTANYS Y D. IGOR ŠTIRN

Garantizamos, al firmar esta tesis doctoral, que el trabajo ha sido realizado por el doctorando bajo la dirección de los directores de la tesis y hasta donde nuestro conocimiento alcanza, en la realización del trabajo, se han respetado los derechos de otros autores a ser citados, cuando se han utilizado sus resultados o publicaciones.

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Directores de la Tesis

Fdo.: Belén Feriche Fernández-Castanys

Fdo.: Igor Štirn

Doctorando

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ABBREVIATIONS

1RM	1-repetition maximum
asl	Above sea level
AT	Altitude training
BW	Body weight
COM	Centre of mass
CV	Coefficient of variation
CI	Confidence interval
CMJ	Countermovement jump
ES	Effect size
FPV	Final propulsive velocity
FiO_2	Fraction of inspired oxygen
GRF	Ground reaction force
H	Hypoxia
ICC	Intraclass correlation coefficient
LED	Light emitting diode
LVT	Linear velocity transducer
P_{max}	Maximum power
P_{mean}	Mean power
V_{max}	Maximum velocity
MVIC	Maximal voluntary isometric contraction
MLR	Multiple linear regression
N	Normoxia

O_2	Oxygen
RPE	Rating of perceived exertion
SLT	Sea level training
SJ	Squat jump
SEE	Standard Error of the Estimate
$V_{take\text{-}off}$	Take off velocity
F_0	Theoretical maximum force
P_0	Theoretical maximum power
V_0	Theoretical maximum velocity

ABSTRACT

Altitude training plays an important role in the physical preparation of athletes around the world with the expectation of improving sea level performance. Traditionally, research about altitude training has focused on endurance performance and related parameters (e.g., maximum oxygen consumption, total haemoglobin mass, etc). The effectiveness of altitude training strategies in the development of endurance performance is generally recognised (Bonetti & Hopkins, 2009). However, the effect of altitude training on the performance of explosive actions remains virtually unexplored. Swimmers are amongst the athletes who use altitude training most often. Therefore, it is reasonable to explore the effects of a traditional altitude training camp held at moderate altitude (2320 m asl) on swimming start performance, which is the swimming skill most dependent on explosive force and lower-body muscular power.

The main objective of the present Doctoral Thesis was to examine the effect of altitude training on unloaded and loaded jump squat and swimming start performance. In addition, the present research work also aimed to refine the methodology of strength testing and to explore the relationship between different strength manifestations and swimming start performance.

To achieve these purposes, different groups of high level athletes (swimmers from the Slovenian national team, swimmers from the Spanish junior national team, and athletes from different combat sports) participated in the nine studies compiled in the present Doctoral Thesis. Along these studies, the performance of explosive actions such as vertical jumps, bench press, and swimming start performance were assessed in normoxia and after the acute and chronic exposure to a moderate altitude (*Studies V-IX*). Additionally, the simultaneous

use of a force platform and a linear velocity transducer allowed us to refine the methodology of loaded vertical jump testing (*Studies I-II*). Finally, we studied the force derived variables during the push-off phase and swimming start time in swimming starts to identify the best predictors of swimming start performance (*Studies III-IV*).

The primary findings of the present Doctoral Thesis revealed that: (I) the maximum velocity of the bar can be used to predict vertical jump height; (II) the linear velocity transducer is a valid measurement method to assess loaded squat jump performance; (III) the horizontal take-off velocity is the push-off variable most related with swimming start time; (IV) the peak velocity reached during the loaded squat jump proved to be the best indicator of swimming start time; (V) squat jump and bench press performance improve after an acute ascent to altitude; (VI) swimmers that are able to jump higher with additional loads relative to their body weight have a faster swimming start time. In addition, an improvement in vertical jump height following a short-term training program can be used to predict changes in swimming start performance; (VII) the implementation of a power-oriented resistance training during a stay at moderate altitude might enhance the performance of explosive actions such as the loaded squat jump and swimming start time; (VIII) the increase in the maximal mechanical capabilities of leg extensors muscles to generate power after an acute ascent to terrestrial altitude is caused by an increase in the theoretical maximal velocity with no significant changes for maximum force capabilities; and (IX) a typical living high – training high strategy oriented towards the improvement of general strength and endurance capacity has trivial effects on muscular function.

RESUMEN

El entrenamiento en altura juega un papel importante en la preparación física de los atletas de todo el mundo con la expectativa de mejorar el rendimiento a nivel del mar. Tradicionalmente, la investigación sobre el entrenamiento en altura se ha centrado sobre el rendimiento de resistencia y parámetros relacionados (ej., consumo máximo de oxígeno, masa total de hemoglobina, etc.). La efectividad de la estrategias de entrenamiento en altura sobre el desarrollo del rendimiento de resistencia es generalmente aceptado (Bonetti & Hopkins, 2009). Sin embargo, el efecto del entrenamiento en altura sobre el rendimiento de acciones explosivas está prácticamente inexplorado. Los nadadores están entre los atletas que utilizan el entrenamiento en altura con más frecuencia. Por tanto, es razonable explorar los efectos de un campamento tradicional de entrenamiento en altura moderada (2320 m sobre el nivel del mar) sobre el rendimiento en la salida de natación, que probablemente sea la fase de la carrera más dependiente de la fuerza explosiva y potencia de los miembros inferiores.

El principal objetivo de la presente Tesis Doctoral fue examinar el efecto del entrenamiento en altura sobre el rendimiento del salto vertical y la salida de natación. Además, el presente trabajo de investigación también trató de refinar la metodología de la evaluación de la fuerza y explorar la relación entre diferentes manifestaciones de fuerza y el rendimiento en la salida de natación.

Para alcanzar estos objetivos, varios grupos de atletas de alto nivel (nadadores de la selección eslovena, nadadores del equipo junior de la selección española, y atletas de diferentes deportes de combarte) participaron en los nueve estudios que componen la presente Tesis Doctoral. En estos estudios el rendimiento en acciones explosivas como saltos

verticales, press de banca, y el rendimiento de la salida de natación se ha evaluado en normoxia y después de una exposición aguda y crónica a una altitud moderada (*Estudios V-IX*). Además, el uso simultaneo de una plataforma de fuerzas y un transductor lineal de velocidad nos ha permitido refinar la metodología de la evaluación del salto vertical sobrecargado (*Estudios I-II*). Finalmente, hemos estudiado las variables derivadas del registro de una plataforma de fuerza durante la fase de impulso de la salida de natación y el tiempo de salida para identificar los mejores predictores del rendimiento de la salida de natación (*Estudios III-IV*).

Los principales hallazgos de la presente Tesis Doctoral revelaron que: (I) la velocidad máxima de la barra puede usarse para predecir la altura de salto vertical; (II) el transductor lineal de velocidad es un instrumento de medición válido para evaluar el rendimiento del squat jump sobrecargado; (III) la velocidad de despegue horizontal es la variable de la fase de impulso más relacionada con el tiempo de salida en natación; (IV) la velocidad máxima alcanzada durante el squat jump sobrecargado resultó ser el mejor indicador del rendimiento en la salida de natación; (V) el rendimiento en los ejercicios de salto vertical y press de banca mejora tras un ascenso agudo a la altitud; (VI) los nadadores que son capaces de saltar más alto con cargas adicionales relativas a su peso corporal tienen un tiempo de salida más rápido. Además, el cambio en la altura de salto vertical tras un programa de entrenamiento a corto plazo puede ser utilizado para predecir cambios en el rendimiento de la salida de natación (VII) la implementación de un programa de entrenamiento de fuerza orientado hacia la mejora de la potencia durante una estancia en altura moderada puede mejorar el rendimiento de acciones explosivas como el salto vertical y el tiempo de salida de natación; (VIII) el incremento de las propiedades mecánicas máximas de los músculo para producir potencia observado tras un ascenso agudo a la altura es causado por un incremento en la máxima velocidad teórica, no existiendo cambios significativos para la máxima producción de fuerza teórica; y (IX) una estrategia típica de entrena alto – vive alto orientada hacia la mejora de la fuerza general y la resistencia tiene efectos triviales sobre la función muscular.

INTRODUCTION

Altitude training plays an important role in the physical preparation of athletes around the world (Bonetti & Hopkins, 2009). Proof of this is that, worldwide, there are at least 22 altitude training centres located between 1000 and 3000 m asl. Swimmers are amongst those athletes who use altitude training most often (Rodriguez et al., 2015). The High Performance Centre of Sierra Nevada is a popular centre for swimmers because of its location (2320 m asl; an optimal altitude according to Bonetti & Hopkins (2009) and Wilber, Stray-Gundersen, & Levine (2007)) and because it is one of the few altitude training centres in the world (the only one in Europe) with a 50-m pool. More than 300 swimmers of 12 different nationalities participated during 2015 in training camps at Sierra Nevada (usually 2-4 weeks duration) with the expectation of improving sea level performance.

In altitude training research using swimmers or other athletes as participants, most of the attention has been focused on endurance performance and related parameters (e.g., maximum oxygen consumption, total haemoglobin mass, etc.) (Govus, Garvican-Lewis, Abbiss, Peeling, & Gore, 2015; Rodriguez et al., 2015). However, the effect of altitude training on muscle power and strength has received much less attention. In this context, the present Doctoral Thesis has attempted to explore the effect of acute and chronic exposure to moderate altitude on the performance of explosive actions, such as vertical jumps and the swimming start. Additionally, we have also aimed to establish the association between different strength manifestations and swimming start performance, as well as to refine the methodology of strength testing using a force plate and a linear velocity transducer as the measurement methods. A brief Introduction of each of the topics covered in the present Doctoral Thesis is presented below:

- **Refining the methodology of strength testing**

The force platform is recognised as the 'gold standard' for testing vertical jumps (Cronin, Hing, & McNair, 2004; Giroux, Rabita, Chollet, & Guilhem, 2015). Namely, by using the direct dynamic approach, the force platform accurately estimates the velocity, power, and position of the system center-of-mass from the directly recorded ground reaction force data. Due to some potential limitations of the force platform (e.g., high cost or the assessments limited to laboratory settings), more affordable and versatile measurement methods have being increasingly used by sport practitioners (McMaster, Gill, Cronin, & McGuigan, 2014). Among those methods arguably the most popular one has been the linear position transducer (Harris, Cronin, Taylor, Boris, & Sheppard, 2010). Specifically, the linear position transducer typically attached to a barbell, derive its velocity, force, and power from the directly recorded displacement-time data using the inverse dynamic approach. However, of importance for further considerations could be that the successive manipulation of raw data typically increase measurement errors (McMaster et al., 2014). In this regard, the first linear velocity transducers, as the one used in the present Doctoral Thesis (T-Force System), have appeared on the market to minimise the number of calculations needed to obtain the kinetic and kinematic variables of interest.

The key outcome when testing vertical jumps arguably is jump height. However, a shortcoming of linear transducers is that they do not offer jump height measurements because they cannot determine the duration of the flight phase or the take-off velocity of the centre of mass. Therefore, it would be interesting to find a way to predict jump height based on the movement velocity, which is directly measured by linear velocity transducers. Because the linear velocity transducer is increasingly used for strength testing, it would also be of interest to examine the correlations and magnitude differences of the main muscle mechanical outputs (i.e., force, velocity, and power) respect to the force plate measurements.

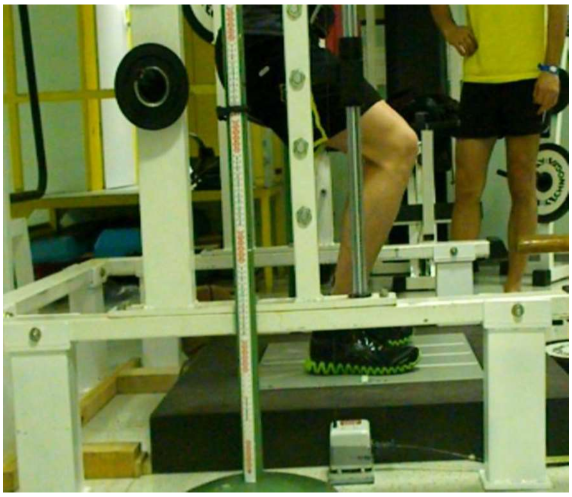

Figure 1. *Swimmer ready to perform the squat jump in the Smith machine.*

- **Association between different strength manifestations and swimming start performance**

The ability to perform a good start has a paramount importance in elite competitive sprint swimming performance (Arellano, Brown, Cappaert, & Nelson, 1994; Mason & Cossor, 2000). Overall swimming start performance, commonly described as the time to 15 m (Barlow, Halaki, Stuelcken, Greene, & Sinclair, 2014; Seifert et al., 2010), is determined by a combination of the following variables: reaction time, horizontal and vertical force applied on the block, low resistance during underwater gliding, and underwater leg propulsion (Elipot et al., 2009; West, Owen, Cunningham, Cook, & Kilduff, 2011). Muscular power and strength are key in order to improve the ability of exerting force against the starting block and the leg propulsion phase, and consequently improving swimming start time (West et al., 2011). Coaches are aware of this fact, and currently swimmers devote a significant part of their training schedule performing resistance training (Bishop et al., 2013).

Many different variables have been used to determine the ability of the swimmer to exert force during the swimming start push-off phase: peak horizontal force (Kilduff et al., 2011; West et al., 2011), peak vertical force (Kilduff et al., 2011; West et al., 2011), resultant take–off velocity (Benjanuvatra, Edmunds, & Blanksby, 2007; Breed & Young, 2003), horizontal take–off velocity (Slawson, Conway, Cossor, Chakravorti, & West, 2013), take–off angle (Barlow et al., 2014; Benjanuvatra et al., 2007; Breed & Young, 2003; Seifert et al., 2010), block time (Barlow et al., 2014; Benjanuvatra et al., 2007; Breed & Young, 2003; Seifert et al., 2010; Slawson et al., 2013), movement time (Barlow et al., 2014; Benjanuvatra et al., 2007), vertical impulse (Benjanuvatra et al., 2007; Breed & Young, 2003), horizontal impulse (Benjanuvatra et al., 2007; Breed & Young, 2003), average horizontal acceleration (Slawson et al., 2013), and peak horizontal acceleration (Slawson et al., 2013), among other variables, have all been used for this purpose. This fact could suggest a lack of consensus between different researchers about which of the variables that can be collected with a force plate during the push-off phase are the most important to determine swimming start performance.

There is consensus within the scientific literature about the suitability of possessing high levels of muscular power and strength in order to optimise swimming start performance (C. Bishop et al., 2013; West et al., 2011). In this regard, it would be of interest to determine which strength manifestations (e.g., explosive dynamic force, explosive-elastic dynamic force, maximum and explosive isometric force) are more associated with swimming start performance.

Figure 2. *Swimmer standing on a force plate ready to perform a maximum track start.*

- **Effect of altitude training on the performance of explosive actions**

Chronic exposure to altitude has been related to a deterioration in lean mass (Deldicque & Francaux, 2013; Mizuno, Savard, Areskog, Lundby, & Saltin, 2008) and its functional capacity (Felici et al., 2001; Ferretti, Hauser, & di Prampero, 1990; Narici & Kayser, 1995; Raguso, Guinot, Janssens, Kayser, & Pichard, 2004). The effect of hypoxia itself on protein metabolism (Deldicque & Francaux, 2013; Etheridge et al., 2011), an insufficient energy intake (Aeberli et al., 2013; Fulco et al., 2002) or a reduced training stimulus (Feriche et al., 2014; Hoppeler & Desplanches, 1992) have been identified as possible explanations for these impairments. However, the studies that have found adverse effects of chronic hypoxia on the muscle size and strength/power adaptations have been conducted at higher altitude (> 5000 m asl) than the 2000-2500 m commonly recommended to optimise physiological adaptations (Bonetti & Hopkins, 2009; Wilber et al., 2007).

Contrary, an acute ascent in altitude has been related to an improvement in the performance of explosive actions (Hamlin, Hopkins, & Hollings, 2015; Kenney, Wilmore, & Costill, 2012). For example, Chirosa et al. (2006) reported an increased velocity against the same absolute load during the half-squat exercise following a sudden ascent (within 1-5 hours) to moderate altitude (2320 m asl) from normoxic conditions. The reduction in the external resistance to the movement due to the decrease in air density at altitude has been proposed as the principle explanation for these results (Hahn & Gore, 2001; Kenney et al., 2012; Levine, Stray-Gundersen, & Mehta, 2008; Peronnet, Thibault, & Cousineau, 1991). However, different physiological factors such as an additional recruitment of fast twitch muscle fibres (Schoenfeld, 2013) or the increased activity of the sympathetic nervous system (Hainsworth et al, 2007) could also be implicated. Therefore it is of interest to study the effect of chronic exposure to a moderate natural altitude (2000–2500 m asl) on muscle power adaptations.

The force–velocity relationship of muscles performing multi-joint tasks (e. g., bench press, vertical jumps, etc.) is currently being used to study the maximal mechanical capabilities of the human musculoskeletal system to generate force, velocity, and power (Cuk et al., 2014; Garcia-Ramos, Jaric, Padial, & Feriche, 2016; Jaric, 2015; P Samozino et al., 2014). Because previous studies that have described an increase in the velocity at which a determined absolute load can be lifted at altitude used a linear transducer as the measurement method, it is not possible to identify whether athletes actually applied more force at altitude or if these results were caused by the lower air resistance. Therefore, it would be interesting to compare the performance of functional movements (e.g., vertical jumps) at sea level and altitude conditions when the force applied is directly recorded with a force platform.

In addition, whether the enhanced performance in explosive actions described in altitude is maintained after a chronic exposure to altitude is unknown. Similarly, there is a shortage of knowledge about the development in explosive actions performance after a training camp at moderate altitude. Therefore, it would be of interest to evaluate the influence of altitude training on explosive actions performance such as the swimming start and loaded SJ performance in high level swimmers, which are one of the athletes that use altitude training more assiduously.

AIMS AND HYPOTHESES

A) General aims

The major aims of the present Doctoral Thesis were:

1. To study the effect of an acute and chronic exposure to a moderate hypoxia on lower-body muscular function.

2. To describe the typical resistance training routines of high level swimmers during prolonged stays at moderate terrestrial altitude.

3. To establish the association between different strength manifestations and swimming start performance.

4. To provide the basic knowledge for athletes that performs resistance training under hypobaric hypoxia conditions.

B) Specific aims and hypotheses

The outcomes of this Doctoral Thesis have been organized in nine studies, based on the following specific aims and hypotheses:

- **Study I:** To predict vertical jump height from the velocity of the bar directly recorded by a linear velocity transducer. Based on the high correlation previously reported between force plate and linear transducer measurements (Crewther et al., 2011), we hypothesised that the velocity recorded by the linear velocity transducer would estimate jump height with acceptable precision.

- **Study II:** To correlate, compare, and determine the reliability of force, velocity, and power values collected with a force plate and a linear velocity transducer during loaded squat jumps performed in a Smith machine. It was hypothesised that (a) the correlations between both measurement tools would be greater than previously reported during free-weight jump squats, (b) the differences between force plate and linear velocity transducer would be dependent on the external load, and (c) the intraday reliability would be higher for peak values because they are less influenced by arbitrary decisions about how to determine the start and end of the concentric phase (Naruhiro Hori et al., 2007).

- **Study III:** To determine the relationship between different variables assessed with a force plate during the starting push-off phase and the times to 5, 10 and 15 m. We hypothesised that the horizontal take-off velocity would be the push-off variable most related to swimming start time.

- **Study IV:** To identify the dry land test most related to swimming start performance (time to 5, 10 and 15 m). These dry land tests evaluated different strength manifestations: explosive dynamic force (SJ), explosive-elastic dynamic force (CMJ), maximum and explosive isometric force (MVIC). We hypothesised that vertical jumps would be more related to swimming start performance than the isometric tests, because its pattern of movement is more similar to the swimming start push-off phase.

- **Study V:** To compare the effects of an acute exposure to terrestrial (hypobaric hypoxia) or simulated (normobaric hypoxia) moderate hypoxia on the force-velocity relationship observed in the bench press exercise. We hypothesized that higher differences respect to normoxic conditions would be obtained in hypobaric hypoxia condition because the lower barometric pressure at terrestrial altitude reduces air resistance.

- **Study VI:** The objective of the study VI was threefold: (a) to analyse the development in squat jump height and swimming start performance after an altitude training camp, (b) to correlate jump height and swimming start performance before and after the altitude training period, and (c) to correlate the percent change in squat jump height with the percent change in swimming start performance following the altitude training camp. It was hypothesised that (a) jump height and swimming start time would improve after the altitude training camp, (b) the swimmers which are able to jump higher during unloaded and loaded (additional loads relative to body weight) squat jumps would be those with better start performance; and (c) the swimmers with higher enhancements in vertical jump height after the altitude training camp would be also those with larger enhancements in swimming start time.

- **Study VII:** The aims of study VII were (a) to compare loaded squat jump performance after an acute (1-3 days) and chronic (15-17 days) exposure to a moderate natural altitude between normoxia and hypobaric hypoxia conditions, and (2) to analyse the effect of an altitude training camp on loaded jump squat development. It was hypothesised that (a) the improvements in loaded squat jump performance at altitude compared to normoxia conditions would be similar after an acute and chronic exposure to a moderate natural altitude, and (b) the altitude training period would induce an improvement in vertical jump performance.

- **Study VIII:** The aims were (a) to analyse the effect of an acute exposure to real altitude on the F–V relationship parameters (maximum force [F_0)], maximum velocity [V_0)], and maximum power [P_0)]) during the loaded SJ, and (b) to compare unloaded SJ and CMJ performance between sea level and altitude conditions. We hypothesised that the mechanical variables recorded by the force plate would be also higher at altitude.

- **Study IX:** To evaluate the influence of an altitude training camp on swimming start times and loaded SJ performance in high level swimmers following a concurrent training regime mainly oriented towards the improvement of endurance capacity. The training regime followed by the swimmers when ascends to train at altitude is generally oriented towards the improvement of endurance capacity. It is known that concurrent endurance training attenuates strength training responses (Rønnestad, Hansen, & Raastad, 2012). In this regard, Häkkinen et al. (2003) reported that concurrent strength and endurance training leads to interference in explosive strength development. Therefore, it is possible that this type of training attenuates the adaptations in explosive actions such as the vertical jump and the swimming start skill. Therefore, we hypothesised that a traditional altitude training camp oriented towards the improvement of endurance capacity would elicit trivial changes in the performance of explosive actions.

MATERIAL AND METHODS

The material and methods section of the present Doctoral Thesis is briefly described in Table 1. Further information of the material and methods section (participants, design, testing and training procedures, and statistical analyses) of each of the nine studies conducted to address the specific aims of the present Doctoral Thesis is also provided. Note that the procedures that are repeated between the different studies are only described in the first study in which they appear.

Table 1. Summary of the main methodological features of the studies included in the present doctoral thesis.

Study	Design	Participants	Procedure	Statistical analysis
I. Predicting vertical jump height from bar velocity	Correlational study	30 swimmers (23 women, 7 men)	SJ incremental loading test	Simple linear regression
II. Comparison of the force-, velocity-, and power-time curves recorded with a force plate and a linear velocity transducer	Correlational study	23 female swimmers	SJ incremental loading test	2-way repeated measures ANOVA and Pearson's correlation coefficients
III. Relationship between different push–off variables and start performance in experienced swimmers	Correlational study	21 female swimmers	Freestyle and undulatory swimming start	Multiple linear regression
IV. The relationship between the lower-body muscular profile and swimming start performance	Correlational study	20 female swimmers	Freestyle start, unloaded SJ and CMJ, loaded SJ, and leg extension and leg flexion MVIC	Pearson's linear correlation coefficient
V. Effect of acute exposure to moderate	Crossover	28 Olympic	Bench press incremental	Paired samples t-tests,

altitude on muscle power: hypobaric hypoxia vs normobaric hypoxia	design	combat sports athletes	loading test. Hypobaric hypoxia versus normobaric hypoxia.	Wilcoxon, and Mann-Whitney U tests
VI. Relationship between vertical jump height and swimming start performance before and after an altitude training camp	Cohort study	15 male swimmers	SJ incremental loading test and undulatory swimming start	2-way repeated measures ANOVA and Pearson's correlation coefficients
VII. The effect of acute and chronic exposure to hypobaric hypoxia on loaded squat jump performance	Cohort study	16 male swimmers	SJ incremental loading test	3-way repeated measures ANOVA
VIII. The maximal mechanical capabilities of leg extensors muscles to generate velocity and power improve at altitude	Crossover design	17 swimmers (12 women, 5 men)	SJ incremental loading test, and unloaded SJ and CMJ	Paired samples t-tests and effect sizes
IX. Relationship between vertical jump height and swimming start performance before and after an altitude training camp	Crossover design	13 swimmers (8 women, 5 men)	SJ incremental loading test and freestyle swimming start	2-way repeated measures ANOVA and effect sizes

Study I

Predicting vertical jump height from bar velocity

Participants

The study population was comprised of 30 swimmers, 23 women (age 16.0 ± 2.7 years, height 166.8 ± 5.8 cm, body mass 57.6 ± 7.1 kg), and 7 men (age 18.0 ± 3.3 years, height 180.7 ± 3.7 cm, body mass 68.2 ± 6.2 kg) from the Slovenian national team.

Design

A correlation study was designed to predict jump height according to bar velocity. Participants performed the loaded SJ at 25%, 50%, 75% and 100% of body weight on a portable force platform with a linear velocity transducer attached to the barbell. The take-off velocity ($V_{\text{take-off}}$) provided by the force platform data was used to determine jump height. The two velocity values used to estimate jump height, maximum velocity (V_{max}) and final propulsive velocity (FPV), were provided by the linear velocity transducer.

Testing procedures

After a 10-min standardised warm-up based on jogging, joint mobility, dynamic stretching, 6 jumps without additional weight, and 1 set of 5 SJ with an unloaded Smith machine bar (16 kg), the swimmers completed an incremental loading test during the SJ exercise at 25%, 50%, 75% and 100% of their own body weight in a Smith machine. Two trials with each load were performed, but only the data of the jump with the greater $V_{\text{take-off}}$ entered in the analysis. Rest periods were one minute between trials using the same load and five minutes between trials using different loads.

The loaded SJ exercise commenced from a standing position with the knees and hips fully extended, feet approximately shoulder-width apart, and the barbell resting across the back at the level of the acromion. The swimmers then slowly descended until the back of the thigh touched an elastic cord set at a knee angle of 90º (McBride, Haines, & Kirby, 2011). The knee angle was set with a manual goniometer. The subjects were instructed to maintain this position for two seconds before performing a purely concentric action in order to jump as high as possible (Markovic & Jaric, 2007). Movements such as countermovement or throwing the bar over the shoulders were not allowed. If any of these movements were observed, the jump was repeated after the corresponding period of rest.

The force platform and the linear velocity transducer were simultaneously used as follows:

- *Force platform.* All jumps were performed on a portable force platform (AMTI, Watertown, MA, USA) mounted according to the manufacturer's specifications. The device's proper calibration was checked before and after each testing session. The force platform was positioned in the centre of the Smith machine and stabilized using a solid wooden base that was flush with the force platform surface. The ground reaction force, which was recorded with a frequency of 1,000 Hz, was used to calculate $V_{take\text{-}off}$ according to the impulse-momentum theorem. The impulse (force x time) recorded at each time point (1 millisecond) was divided by the subject's mass to determine the system centre of mass change in velocity, which was then added to the system centre of mass prior velocity to give a new instantaneous velocity for that time interval. System centre of mass velocity at take-off was used to calculate jump height using the equation: $Jump\ height = (V_{take\text{-}off})^2 / (2 \times gravity)$.

- *Linear velocity transducer.* A dynamic measurement system (T-Force System; Ergotech, Murcia, Spain) validated by Sánchez-Medina & González-Badillo (2011) was fixed perpendicularly to the bar with a tether to record its vertical instantaneous velocity at a frequency of 1,000 Hz. V_{max} was defined as the maximum instantaneous velocity attained during the concentric phase. FPV was defined as the bar velocity just before the acceleration of the bar was lower than -9.81 $m \cdot s^{-2}$. The propulsive phase of the repetition was defined as the interval between the beginning of the concentric movement and the time when bar acceleration is lower than gravity (-9.81 $m \cdot s^{-2}$) (Sanchez-Medina, Perez, & Gonzalez-Badillo, 2010). Thus, FPV was the velocity recorded in the last millisecond of the propulsive phase.

Statistical analyses

Analysis of variance (ANOVA) with repeated measures and Bonferroni post hoc comparisons were used to examine differences between the three velocities analysed (V_{max}, FPV and $V_{take\text{-}off}$). Jump height was predicted using V_{max} or FPV as the independent variables through simple linear regression. The adjusted Pearson's multivariate coefficient of determination (adj. r^2), the standard error of the estimate (SEE), and the model equation were calculated. Bland-Altman plots of mean differences were constructed to compare: a) $V_{take\text{-}off}$ with the two velocities recorded by the linear velocity transducer; and b) jump height calculated from the force platform data with jump heights estimated by the two simple linear regression models. All statistical tests were performed using the software package SPSS (version 20.0: SPSS, Inc., Chicago, IL, USA). Significance was set at $P < 0.05$.

Study II

Comparison of the force-, velocity-, and power-time curves recorded with a force plate and a linear velocity transducer

Participants

Twenty-three female swimmers from the Slovenian national team (age 16.0 ± 2.7 years, height 166.8 ± 5.8 cm, body mass 57.0 ± 7.0 kg) participated in this study.

Design

The validity of a linear velocity transducer to measure loaded SJ performance was determined by comparing and correlating the mean and peak values of force, velocity, and power output with data obtained simultaneously with a force plate.

Testing procedures

The general characteristics of the loaded SJ test are provided in Study I. Vertical force, velocity, and power during loaded squat jump were evaluated simultaneously using a kinetic (force plate) and a kinematic system attached to the barbell (LVT).

- *Force plate.* Jump squats were performed on a portable force plate (AMTI, Watertown, MA, USA). The ground reaction force (GRF) data was collected at a frequency of 1,000 Hz and was used to calculate the variables of interest by the impulse-momentum approach. The impulse (force x time) of each elementary time segment (1 ms) was divided by the system mass to determine the system COM change in velocity, which was then added to the system COM's previous velocity to produce a new instantaneous velocity for that time interval. Instantaneous power was calculated as the product of GRF and system COM velocity at each time point. For the force plate data analysis, the initiation of the concentric phase was defined as the first instance when GRF was 105% of system weight (body weight + weight of the external load) and the end of the concentric phase was defined as the point at which the GRF dropped under 1% of system weight.

- *Linear velocity transducer.* A dynamic measurement system (T-Force System; Ergotech, Murcia, Spain) was fixed perpendicularly to the bar with a tether and reported its vertical instantaneous velocity at a frequency of 1,000 Hz. With knowledge of bar velocity, the derived mechanical variables were automatically calculated by the software as follows: (a) instantaneous *acceleration* was calculated by differentiating the velocity data with respect to time; (b) instantaneous *force* was calculated as the product of system mass (body mass + mass of the external load) and total acceleration (acceleration due to gravity + acceleration of the barbell); (c) instantaneous *power* was calculated as the product of force and barbell velocity at each time point. For the LVT data analysis, the duration of the concentric phase was automatically settled by the software between the first positive velocity recorded and the instance when acceleration was lower than -9.81 m/s^2 (Hori et al., 2007)

Peak force, peak velocity, and peak power were determined as the maximum instantaneous value achieved during the concentric phase at a given load. Mean force, mean velocity, and mean power were determined as the area under the concentric portion of their respective curves divided by the duration of the repetition. Additionally, the force-, velocity-, and power-time curves were normalised for the total duration of the concentric phase for each measurement tool (Cormie, McBride, & McCaulley, 2009). Force, velocity, and power values at 5% intervals were obtained and then averaged across all participants to create an average curve for each load (Cormie, Deane, & McBride, 2007).

Statistical analyses

Test-retest absolute reliability was measured by the standard error of measurement which was expressed in relative terms through the coefficient of variation (CV), whereas relative reliability was assessed by the intraclass correlation coefficients (ICC) calculated with the two-way random effects model. A two-way (device x load) ANOVA with repeated measures was used to determine the impact of the load on the outcomes measured by the force plate and LVT. When significant F values were achieved, pairwise differences between means were identified using Bonferroni post hoc procedures. Pearson's product moment correlation coefficients (*r*) between peak and mean values of force, velocity, and power recorded by each measurement tool and between tools for each variable were calculated. All statistical tests were performed using the software package SPSS (version 20.0: SPSS, Inc., Chicago, IL, USA). Statistical significance level was set at alpha ≤ 0.05.

Study III

Relationship between different push–off variables and start performance in experienced swimmers

Participants

Twenty–one women from the Slovenian national swimming team (age 16.1 ± 2.8 years, height 167.0 ± 5.7 cm, body mass 57.9 ± 7.4 kg) volunteered to participate in this study.

Design

A correlation study was designed to examine the relationship between different force derived variables measured during the starting push–off phase and start performance (times to 5, 10 and 15 metres) in experienced female swimmers. Participants performed two different swim track starts (freestyle and undulatory) on a portable force plate up to the 15-metre mark.

Testing procedures

After completing a standard warm–up based of their pre–race routine, swimmers were instructed to perform two different track starts until a distance further than 15 meters to ensure representative values of the time to 15 meters (Barlow et al., 2014). A standardized starting procedure was used. Swimmers waited standing on the starting block. When they were ready, a tester gave the command ‘‘take your mark’’, and then was made a sound by crashing a clapperboard to signal the start of the trial. False starts were discarded and the trial was repeated. Recovery time between each trial was five minutes. The characteristics of the two different starts, which were performed in a counterbalanced order, were as follow:

- *Freestyle:* Swimmers were instructed to perform their usual race start until reach the 15 meters mark.

- *Undulatory:* Swimmers were instructed to reach the 15 meters mark through only underwater undulatory kicking, as the one used in the butterfly stroke.

To measure GRF during the start, a portable force plate (Kistler 9253A11, Winterthur, Switzerland) was put on a custom-made stand with an angle of 7º to the horizontal and a custom-made steel starting block (identical to OSB11) was mounted on top of the force plate. Global vertical (F_v) and horizontal (F_h) forces were calculated from the force plate force components as already shown by West at al. (2011). F'_v and F'_h, measured by the inclined force plate, were resolved into vertical and horizontal components F_{v1}, F_{h1}, and F_{v2}, F_{h2}, respectively. The two vertical components (F_{v1} and F_{v2}) and the two horizontal components (F_{h1} and F_{h2}) were then added to given the total vertical and horizontal components, F_v and F_h, respectively, giving:

$$F_v = F'_v \sin 83º + (-F'_h \sin 7º)$$

$$F_h = F'_v \cos 83º + F'_h \cos 7º$$

Global vertical and horizontal forces were used for calculations of GRF parameters. The starting device simultaneously produced sound, visual (light) and electric signal (TTL) which was send to a computer and used to synchronise the kinematic data and the data collected with the force plate.

Two underwater cameras (GoPro Hero 3, Go Pro Inc. San Mateo, California, USA) and an overwater camera (Casio Exilim Pro EX-FX1, Casio Computer CO., LTD. Tokyo, Japan) were set up such that their optical axes were perpendicular to the direction of swimming at 5, 10 and 15 metres from the starting position, respectively. The GoPro cameras were configured to record 100 frames per second, with a field of view equivalent to 28 mm, and a resolution of 1280 × 720 pixels. The Casio EX-FX1 camera was configured to record 300 frames per second, with a focal length of 80 mm, and a resolution of 512 × 384 pixels. All the cameras were synchronised with the starting signal. A wooden clapperboard was used to synchronize the system. The clapperboard emitted an acoustic signal used as the starting signal and simultaneously a light-emitting diode (LED) device was activated. This device consisted of a waterproof rope containing LED lights at one-metre intervals that was extended from one end of the pool to the other at a depth of one metre. Each camera was able to record at least one of the LEDs that were activated together with the acoustic starting signal. When processing the data, the first frame in which the LEDs are switched on was used to determine the zero time of the video recordings. To ensure reliable and valid data collection a 2D reference system was built. Three non-elastic ropes of 5.5 metres length were hooked on a gangway located 4 metres above the water's surface. These ropes were set at 5, 10 and 15 metres from the starting end of the pool, corresponding to the distances analysed. A 5 kg dumbbell was attached at the lower end of each rope in order to ensure a strictly vertical line. These ropes were vertically submerged 1.5 metres into the swimming pool. Therefore, each camera was located parallel to each one of the ropes.

Customised software was used to calculate the variables of interest during the push–off phase through the impulse–momentum approach:

Reaction time was defined as the time between the starting signal and a change (positive or negative) in either the horizontal or vertical component of GRF from the stationary body weight signal immediately after the starting signal. *Movement time* was defined as time between the reaction time (change in GRF) and the end of the push-off (GRF dropped to 0). *Push–off time* was the sum of reaction and movement time. *Horizontal force impulse* was calculated using the equation $FI_h = \sum_s^e F_h \Delta t$ where s stands for the instant of the start of the force change, e for the end of push-off and Δt for 1/1000 s as frequency of data acquisition was 1000 Hz. *Vertical force impulse* was calculated using the equation $FI_v = \sum_s^e (F_v - m_b g)\Delta t$ where m_b stands for the body mass. *Horizontal velocity* was calculated from corresponding force impulse divided by body mass (m_b) ($v_h = \frac{FI_h}{m_b}$) and *vertical velocity* from corresponding force impulse divided by body mass (m_b) ($v_v = \frac{FI_v}{m_b}$). *Take–off angle* was calculated according to formula:

$$\propto = arc\tan\frac{v_v}{v_h}$$

Average horizontal force was calculated as horizontal impulse divided by movement phase time. *Average vertical force* was calculated as vertical impulse divided by movement phase time. *Peak horizontal force* was the greatest horizontal force reached during the movement phase. *Peak vertical force* was the greatest vertical force reached during the movement phase. *Resultant impulse* was calculated from component's impulses using Pythagorean Theorem. *Resultant take–off velocity* was calculated as resultant impulse divided by body mass. *Average horizontal acceleration* was calculated as average horizontal force divided by body mass. *Average vertical acceleration* was calculated as average vertical force divided by body mass. *Peak horizontal acceleration* was calculated as peak horizontal force divided by body mass. *Peak vertical acceleration* was calculated as peak vertical force divided by body mass.

The time to 5, 10 and 15 metres were defined as the time elapsed from the starting signal until the swimmer's head crossed the 5, 10 and 15 metres marks, respectively. The analysis was done by the Ultimate Pen Software (St Paul, Minnesota, USA) which allowed us to play the video image as well as to plot the spatial references determined from the 2D reference system. The implementation of a routine (Script) in the Filemaker Pro v.12 software (Santa Clara, California, USA) enabled the time code of the video image to run with QuickTime Player v7 (Cupertino, California, USA) and set this time in its specific database field for further processing.

Statistical analyses

The t–test for paired data and the standardized mean difference (Cohen´s d effect size; ES) were used to compare the two starts performed (freestyle and undulatory). Correlations between all push–off variables and start performance (times to 5, 10 and 15 meters) in the two starts were quantified through Pearson's product-moment correlation coefficient (r). In addition, multiple linear regression analysis was used to find the push–off factors showing an effect on start performance. The best-fit model was generated through stepwise regression ($F_{in} \leq 0.05$; $F_{out} \geq 1.0$) using the times to 5, 10 and 15 meters as the dependent variables, and the push–off variables not dependent to body mass as predictor variables. The adjusted Pearson's multivariate coefficient of determination (adj. r^2), the standard error of the estimate (SEE), the regression constant (a), the raw-score (b) and the standardized coefficients (β-weights) are reported. All statistical tests were performed using the software package SPSS (version 20.0: SPSS, Inc., Chicago, IL, USA). Significance was set at an alpha level of $p < 0.05$.

Study IV

The relationship between the lower-body muscular profile and swimming start performance

Participants

Twenty women (age 15.3 ± 1.6 years, body height 166.9 ± 5.9 cm, body mass 57.2 ± 7.4 kg) from the Slovenian national team participated in this study.

Design

A correlation study was designed to examine the relationship between different dry land strength and power tests and freestyle track start performance (times to 5, 10 and 15 m).

Testing procedures

A) Swimming start

Swimmers were instructed to perform a freestyle track start until a distance further than 15 m as described in Study III. The characteristics of the materials and methods used to determine the times to 5, 10, and 15 m are also describe in the Study III.

B) Unloaded squat and countermovement jumps

Three trials of the SJ and other three of the CMJ were performed on a force plate (Kistler 9253A11, Winterthur, Switzerland) with one min of recovery between them. The ground reaction force data was collected at a frequency of 1000 Hz and was used to calculate the vertical take–off velocity, peak force, and peak power by the impulse-momentum approach.

The characteristics of the jumps, which were performed in a counterbalanced order, were as follow:

- *Squat Jump:* Subjects began from a half squat position (knees and hips flexed at 90º), with hands placed on hips. The subject executed the jump with maximum effort without countermovement and without the swing of the arms.

- *Countermovement Jump:* Subjects began from a fully extended position (knees and hips at 180º) with hands on hips. On the tester's command, a countermovement (knee and hip flexion to 90º) was performed prior to a maximal vertical jump.

Knee angle was measured with a goniometer to 90º, and an elastic cord was set at the participant's buttocks. A trial was deemed successful if the participant reached the depth of the elastic cord. The trial was repeated if the participant was too shallow or squatted deeper than the elastic cord (García-Ramos et al., 2015b).

C) Squat jumps with additional weights

The general characteristics of the loaded SJ test that was performed at 25, 50, 75 and 100% of subject's BW are provided in Study I. A linear velocity transducer (T-Force System; Ergotech, Murcia, Spain) also described in Study I was used to determine the variables of interest. Peak vertical force, peak vertical velocity, and peak vertical power were determined as the maximum instantaneous value achieved during the concentric phase for each load. In addition, peak force and peak power outputs were normalized with respect to swimmer's body mass.

D) Maximal voluntary isometric contractions

The maximum voluntary isometric knee extension and flexion were performed at 60º and 40º of knee angle (0° = full extension), respectively. The hip angle was fixed at 110°. Subjects sat in the isometric knee torque measuring device equipped with force transducer (MES, Maribor, Slovenia) (Tomazin et al., 2008). The back was supported and the hips were firmly fixed, the rotational axis of the dynamometer was visually aligned to the rotational axis of the knee (i. e., lateral femoral epicondyle) and the lower leg was attached to the dynamometer lever arm above the ankle joint (i. e., lateral malleolus). During the measurements the subjects were also instructed to hold onto arm supports on both sides of the rigid chair to further stabilize the pelvis.

Two progressive and two explosive isometric knee extensions and flexions in random order were performed. The rest periods between the contractions were 1 min. During progressive contraction the maximum torque was achieved in two seconds and maintained afterwards for three seconds. However, during the explosive contractions the subjects were instructed to develop maximal torque as soon as possible and maintain it for three seconds. The trial corresponding to the maximum torque (progressive contraction) and the trial corresponding to the highest average torque obtained in the first 200 ms (explosive contraction) were analyzed. The variables analyzed in these tests were the maximum torque determined within an interval of 500 ms (progressive contraction) and the average torque from the onset of the contraction to 200 ms (explosive contraction). Both variables were also normalized according to subject's body mass. The torque signals were recorded with PowerLab system (16/30 - ML880/P, ADInstruments, Bella Vista, Australia) at a sampling frequency of 2000 Hz.

Statistical analyses

Correlations between the different variables collected during the dry land tests and freestyle start performance (times to 5, 10 and 15 m) were quantified through Pearson's linear correlation coefficient (r). Qualitative interpretations of the r coefficients as defined by Hopkins (2002) (0–0.09 trivial; 0.1–0.29 small; 0.3–0.49 moderate; 0.5–0.69 large; 0.7–0.89 very large; 0.9–0.99 nearly perfect; 1 perfect) were provided for all significant correlations. All statistical tests were performed using the software package SPSS (version 20.0: SPSS, Inc., Chicago, IL, USA). Significance was set at an alpha level of $p < 0.05$.

Study V

Effect of acute exposure to moderate altitude on muscle power: hypobaric hypoxia vs normobaric hypoxia

Participants

Twenty-eight male Olympic combat sports athletes (wrestling n = 16, judo n= 7 and taekwondo n = 5) participated in the study.

Design

A repeated measures design was employed with two independent groups (G1 and G2). Subjects in both groups were tested on two occasions separated by a rest period of 48 h. Subjects in G1 were tested first in conditions of normoxia (N1) and then following an ascent to the High Performance Centre of Sierra Nevada at 2320 m asl (HH). Subjects in G2 were first tested in conditions of normoxia (N2) and then after exposure to simulated normobaric hypoxia (NH) at the High Performance Center of Sant Cugat. Simulated NH was achieved by breathing a mixture of air impoverished in oxygen (15.7% FiO_2) corresponding to an altitude of 2300 m. Individual load–velocity relationships were determined during an incremental loading test in the bench press exercise.

Testing procedures

After a standardised warm up protocol, subjects completed an incremental loading test i the bench press exercise. The starting load was 20 kg and this was increased by 10 kg per set until the individual’s 1RM. One set of 2 to 4 repetitions was performed per load. The recovery period between sets was 3 min for velocities >1 m/s or 5 min for velocities < 1 m/s. All the tests were performed in a Smith machine.

Mechanical variables were recorded using a linear position transducer (Real Power Pro Globus, Codgne, Italy linked to a Tesys 400) and Ergo System 8.5 software. The system was fixed to the barbell such that the cable was vertically displaced and informed of the barbell displacement at a frequency of 1000 Hz. For each repetition, we obtained the mean and maximum values of velocity (V) and power (P). Only the best repetition for each load in terms of the greatest mean power generated (P_{mean}) was entered in the subsequent analysis. We established as maximum power (P_{max}), the highest Pmean recorded across the full curve. The load corresponding to P_{max} for each subject was obtained from the load-Pmean polynomic equation constructed using data for the exercise sets comprising the whole test. Subjects assigned to the NH test wore a silicon mask connected to an oxygen depleting respiratory system (HYP100, Hypoxic Inc System, Shekou Shenzhen, China) from 5 min before warm up to test completion.

Statistical analyses

The influence of hypoxia exposure for each group (pre vs. post) on each dependent variable was assessed with paired t-tests. Performance absolute differences on each group (HH-N1 vs. NH-N2) were used to compare hypobaric vs. normobaric hypoxia effects. Wilcoxon and Mann-Whitney U tests were used when data was not normally distributed. The magnitude of the main differences between comparisons was also expressed as standardized mean difference (Cohens d effect size; ES). All statistical tests were performed using the software package SPSS (version 20.0: SPSS, Inc., Chicago, IL, USA). Significance was set at $P < 0.05$.

Study VI

Relationship between vertical jump height and swimming start performance before and after an altitude training camp

Participants

Fifteen male swimmers from the Spanish junior national team (age 17.1 ± 0.8 years, height 181.2 ± 6.5 cm, body mass 74.1 ± 8.0 kg) volunteered to participate in this study.

Design

A repeated-measures design was used to examine the effect of an altitude training camp on the development of SJ height and swimming start performance. Additionally a correlation analysis was conducted to examine the relationship between loaded and unloaded SJ height with swimming start performance before and after the altitude training period. The accuracy of using changes in jump performance to determine changes in swimming start performance that occurred after the training program were also assessed through Pearson's product-moment correlation.

To this end, subjects took part in a training camp of 17 days at the High Performance Centre of Sierra Nevada (Spain) located at 2320 m asl. The swimming tests were conducted in the second (pretest) and sixteenth (postest) days. An undulatory swim start to a distance further than 15 meters was performed each day of testing. The dry land tests were randomly assigned to days 1 (pretest) and 15 (postest) for a group of swimmers, and to days 3 (pretest) and 17 (postest) for the remaining swimmers. The squat jump exercise with additional loads of 0%, 25%, 50%, 75%, and 100% of swimmers' pretest body weight (BW) was performed each day of dry land testing. The time to 5, 10, and 15 meters of the undulatory swimming start and the squat jump height were the dependent variables analyzed.

Testing procedures

A) Swimming test

After completing a standard warm–up based of their pre–race routine, swimmers were instructed to perform a kick start from a starting block (OMEGA OSB11) located at 0.70 meters from the water surface. A standardized starting procedure was used. Swimmers stood on the starting block and when ready were given the command ‘‘take your mark’’ before the starting device sounded. At the sound of the start, audible for the swimmers and visible as a flashing light for the cameras, swimmers initiated the kick start followed by just underwater undulatory kicking (as used in butterfly stroke) at maximum velocity, until a distance further than 15 meters in order to ensure representative values of the time to 15 meters (Barlow et al., 2014; García-Ramos et al., 2015).

The pool where the tests were conducted, had installed an official timing system (ALGE Swim Manager 2000) connected to a light device. Both systems were activated synchronously with the starting signal. This type of synchronization, used in paralympic competitions to provide a visual starting signal to deaf swimmers, was used in the present study to synchronize cameras with the acoustic starting signal. Three underwater cameras (Sensor SONY 1/4 EXView HAD CCD, shutter de 1/600, 100 fps) were set-up such that their optical axes were perpendicular to the direction of swimming at 5, 10, and 15 meters from the starting position.

The time to 5, 10, and 15 meters were defined as the time elapsed from the starting signal until the swimmer's head crossed the 5, 10, and 15 meter marks, respectively. The analysis was made with the software Ultimate Pen (St Paul, Minnesota, USA) which allows the video image to be played while plotting the spatial references determined from the 2D reference system. The implementation of a routine (Script) in the Filemaker Pro v.12 software (Santa Clara, California, USA) enabled us to get the time code of the video image playing in with QuickTime Player v7 (Cupertino, California, USA) and set this time in its specific database field for further processing.

B) Vertical jump test

Swimmers performed an incremental loading test using the squat jump exercise. First, they performed the unloaded squat jump (free weight) with a light bar (0.5 kg) over their shoulders (0% load), in order to keep the posture and the same body position as the rest of the jumps. After that, squat jumps with additional loads of 25%, 50% and 75%, and 100% of the swimmers' pretest BW were lifted in a Smith machine (Technogym, Barcelona, Spain). Two repetitions were performed with each load. Recovery time was one min between attempts with the same load and five min between the different loads. The general characteristics of the loaded SJ technique is described in Study I.

The OptoGait photoelectric system (Optogait 1.9, Microgate, Bolzano, Italy) was used to estimate squat jump height with a sample rate of 1000 Hz. Only the best jump executed at each load, identified according to the criterion of the highest jump height, was considered for subsequent analysis. In addition, an overall jump height value for each swimmer was calculated averaging the jump height values of each individual load ([0%BW + 25%BW + 50%BW + 75%BW +100%BW] / 5).

Training procedures

The swimmers completed the training programs prescribed by their coaches during the 17-day training camp and the training load was monitored by training diaries. The main coach was responsible for filling in the training diary of each swimmer. On average, swimmers performed 25 pool sessions (mean ± standard deviations [SD]; duration: 119.8 ± 10.8 min, CR-10 RPE [9]: 7.3 ± 0.9, and distance: 6696 ± 644 m) and 10 dry land sessions (4 circuits training and 6 strength-power training). The half-squat (3-4 sets of 6-8 repetitions with 70-90% of BW and fast speed) and the lunge (3-4 sets of 6-12 repetitions with 30% of BW and moderate speed) were the lower limb exercises performed by the swimmers. A total of 240 min of the training period (on average a 13.4% of each pool training session) was dedicated to improving starting technique for swimming.

Statistical analyses

A two-way (test [pretest and postest] x load [0%, 25%, 50%, 75%, and 100% of BW]) repeated measures ANOVA was used to compare squat jump height between the different tests performed. Another two-way (test [pretest and postest] x distance [5, 10 and 15 meters]) repeated measures ANOVA was used to examine swimming start performance. When significant F values were achieved, pairwise differences between means were identified using Bonferroni post hoc procedures. The Greenhouse-Geisser correction was used when Mauchly's test of sphericity was violated. The magnitude of the differences was expressed as a standardized mean difference (Cohen's d effect size; ES). The criteria to interpret the magnitude of the ES were as follows: <0.2 = trivial, 0.2–0.6 = small, 0.6–1.2 = moderate, 1.2–2.0 = large, and >2 = very large (W. Hopkins, 2002). Correlations between squat jump height and undulatory swimming start performance (time to 5, 10, and 15 meters) were quantified through Pearson's linear correlation coefficient (r). Qualitative interpretations of the r coefficients as defined by Hopkins (19) (0–0.09 trivial; 0.1–0.29 small; 0.3–0.49 moderate; 0.5–0.69 large; 0.7–0.89 very large; 0.9–0.99 nearly perfect; 1 perfect) were provided for all significant correlations. All statistical tests were performed using the software package SPSS (version 20.0: SPSS, Inc., Chicago, IL, USA). Significance was set at $P < 0.05$ and the confidence interval at 95% is indicated when appropriate (95% CI).

Study VII

The effect of acute and chronic exposure to hypobaric hypoxia on loaded squat jump performance

Participants

Sixteen male swimmers from the Spanish Junior National Team (age 17.1 ± 0.8 years, height 1.81 ± 0.07 m, body mass 73.9 ± 7.8 kg) volunteered to participate in this study.

Design

A repeated-measures design was used to investigate the effect of an acute and chronic exposure to hypobaric hypoxia on loaded squat jump performance. The participants were assessed and monitored over a 17-day period at the High Performance Centre of Sierra Nevada (Spain), located at 2320 m asl. During this period, swimmers were tested four times, two in normoxia (690 m asl) and two in hypobaric hypoxia (2320 m asl). The swimmers were randomly tested in a counterbalanced order on days 1 and 3 (acute exposure) in both normoxia (N_1) and hypoxia (H_1) and again on days 15 and 17 (chronic exposure) in normoxia (N_2) and hypoxia (H_2). The individual load-velocity relationships with loads equivalent to 25%, 50%, 75% and 100% of swimmers' pretest BW in the loaded squat jump exercise was determined on each day of testing. Peak velocity was collected with a linear velocity transducer (T-Force System) to compare the acute effect of altitude exposure (N_1 vs. H_1 and N_2 vs. H_2) as well as the adaptation after the training camp (N_1 vs. N_2 and H_1 vs. H_2).

Testing procedures

After a standardized warm-up, swimmers performed an incremental loading test in the loaded SJ exercise. The loads used were 25%, 50%, 75%, and 100% of the swimmers' pretest BW. The general characteristics of the loaded SJ technique is described in Study I.

A linear velocity transducer (T-Force System; Ergotech, Murcia, Spain) was used to determine the peak velocity of the bar that was defined as the maximum instantaneous velocity value attained during the concentric phase of each repetition. Peak velocity was used since this variable has shown to be closely related to vertical jump performance (i.e., jump height) (García-Ramos et al., 2015). Only the repetition with the highest peak velocity at each load was considered for analysis. In addition, an overall peak velocity value for each subject was calculated by averaging the peak velocity values of each individual load.

Training procedures

The training conducted by the swimmers is described in Study VI.

Statistical analyses

A three-way (test [pretest and postest] × condition [normoxia and hypoxia] × load [25%, 50%, 75%, and 100% of BW]) repeated measures ANOVA was used to examine peak barbell velocity during the different tests performed. When a significant F value was achieved, pairwise differences between means were identified using Bonferroni post hoc procedures. The magnitude of the differences was expressed as a standardized mean difference (Cohen's d effect size; ES). All statistical tests were performed using the software package SPSS (version 20.0: SPSS, Inc., Chicago, IL, USA). Significance was set at $P < 0.05$ and the confidence interval at 95% is indicated when appropriate (95% CI).

Study VIII

The maximal mechanical capabilities of leg extensors muscles to generate velocity and power improve at altitude

Participants

The study population was comprised of 17 swimmers from the Slovenian national team, 12 women (age 17.7 ± 5.3 years, height 1.67 ± 0.05 m, body mass 56.5 ± 5.6 kg), and 5 men (age 19.9 ± 3.7 years, height 1.81 ± 0.03 m, body mass 72.3 ± 4.2 kg).

Design

A repeated-measures design was used to analyze the effect of an acute ascent to altitude on the F–V relationship of leg muscles during loaded (SJ at 25%, 50%, 75%, and 100% of swimmers' body weight [BW]) and unloaded vertical jumps (SJ and CMJ). Swimmers were tested first at sea level (Faculty of Sport of Ljubljana, Slovenia, 295 m above sea level) and 7 days later at terrestrial altitude (High Performance Center of Sierra Nevada, Spain, 2320 m above sea level) during their first 24 hours of altitude exposure.

Testing procedures

Identical testing procedures were followed in both assessment days. 3 trials of the SJ and another 3 of the CMJ were performed on a force platform with 1 min of recovery between them. Subsequently, the swimmers completed an incremental loading test at 25%, 50%, 75%, and 100% of their own BW during the Smith machine SJ exercise The general characteristics of the unloaded SJ and CMJ and the loaded SJ are described in Study I and III, respectively..

A force platform (Kistler 9253A11, Winterthur, Switzerland) was used to evaluate SJ and CMJ performance. The same force platform and a linear velocity transducer (T-Force System; Ergotech, Murcia, Spain) were simultaneously used to assess loaded SJ performance.

- *Unloaded Squat jump and countermovement jump.* The maximum values of force, power, and jump height recorded with the force platform were used to compare SJ and CMJ performance between sea level and altitude conditions. Only the jump with the highest height for each jump-type was considered for analysis.

- *Loaded squat jump*. The maximum values of force and velocity at each load were recorded by a force platform and a linear velocity transducer, respectively. Two trials per load were performed, but only the jump with the highest maximum velocity entered in the analysis. The maximum F–V relationship was assessed from individual force and velocity data obtained under four loading magnitudes according to Sreckovic et al. (32). The data was modelled by a linear regression [$F(V) = F_0 - aV$], where F_0 represents the Force-intercept (i.e., force at zero velocity), a is the slope that corresponds to F_0/V_0, and V_0 is the Velocity-intercept (i.e., velocity at zero force). As a consequence of the linear F–V relationship, maximum power output (P_0) can be calculated as $P_0 = (F_0V_0)/4$.

Statistical analyses

Prior to statistical analysis, the normal distribution of the data (Shapiro-Wilk test) and the homogeneity of variances (Levene test) were confirmed ($P > 0.05$). Paired samples t-tests were conducted to examine if there were differences between both environment conditions (sea level vs. altitude) in the F–V relationship parameters (F_0, a, V_0, and P_0) and in the values of force, jump height, and power recorded during the SJ and CMJ. The magnitude of the differences was expressed as a standardized mean difference (Cohen's d effect size; ES). The criteria to interpret the magnitude of the ES were as follows: <0.2 = trivial, 0.2–0.6 = small, 0.6–1.2 = moderate, 1.2–2.0 = large, and >2 = very large (W. G. Hopkins, Marshall, Batterham, & Hanin, 2009). The linearity of the F–V relationships was assessed through Pearson's product-moment correlation coefficient (*r*). All statistical tests were performed using the software SPSS (version 20.0: SPSS, Inc., Chicago, IL, USA). Significance was set at $P < 0.05$.

Study IX

Relationship between vertical jump height and swimming start performance before and after an altitude training camp

Participants

The study population was comprised of 13 swimmers (8 women, 5 men) from the Slovenian national team. All swimmers were older than 16 years at the beginning of the study.

Design

A controlled trial was designed to assess the effects of a 3-week training camp held at moderate altitude on swimming start time and loaded SJ performance. To accomplish this goal, the same swimmers were tested under both control (Sea Level Training, SLT) and experimental conditions (Altitude Training, AT). The SLT camp was conducted at 295 m asl (Ljubljana, Slovenia) and the AT camp at 2320 m asl (High Performance Centre of Sierra Nevada, Granada, Spain). The SLT camp (February-March 2014) was conducted 1 year before the AT camp (February-March 2015), and all tests were performed before and after a 3-week training period. From the beginning of the study, the national coach was committed to maintaining the same training objectives for both SLT and AT conditions.

Testing procedures

A) Swimming start

Swimmers were instructed to perform a freestyle track start until a distance further than 15 m as described in Study III. The characteristics of the materials and methods used to determine the times to 5, 10, and 15 m are also describe in the Study III. To measure ground reaction force during the start, a portable force plate (Kistler 9253A11, Winterthur, Switzerland) was used as described in Study III. The horizontal take-off velocity was calculated following the standard procedures of calculation described in Study III. The horizontal take-off velocity was selected because it has been identified as the most determinant variable of the push-off phase in terms of overall start time (García-Ramos et al., 2015; Tor, Pease, & Ball, 2015).

B) Loaded squat jump

An incremental loading test using the SJ exercise with additional loads of 25%, 50%, 75%, and 100% of swimmers' body weight was conducted with a Smith machine as described in Study I. A linear velocity transducer (T-Force System; Ergotech, Murcia, Spain) was employed to determine the peak velocity of the bar that was the dependent variable analyzed. Only the jump with the highest peak velocity of each load was considered for further analysis.

Training procedures

The study was carried out during the second macrocycle (short-course season) of the year (February-march 2014 and 2015). The intervention period comprised a mesocycle of 3 weeks during the general preparation phase. Accordingly, it was a condition of participation that the relative training load would not substantially change during the 3-week study phase between years to allow the full assessment of the training intervention without such a confounding factor. To minimize the influence of fatigue, coaches were asked to reduce the training load the day before to the assessment days.

Individualized training plans were developed by the swimmers' coaches, each very experienced in AT. They implemented the training program according to their own experience, swimmer's fitness level, and individual response to altitude. Typically, training schedules included two pool sessions and a dry-land workout six days per week. Throughout the entire duration of the training period, the main coach of the national team (for pool training sessions) and the fitness coach (for dry-land training sessions) were responsible for filling in the training diary of each swimmer. Pool training was described in terms of time and distance swum. Dry-land sessions were described by reporting the main purpose and the content of training. The main purpose was expressed by the selection of a code: 1 for sessions oriented to developing maximum strength; 2 for explosive strength; 3 for endurance strength; 4 for conditioning; 5 for cardiovascular activities; and 6 for range of motion and flexibility. For codes 4 to 6, a brief description of the content was also incorporated. For codes 1 to 3, additional information, such as the number and description of exercises, sets, repetitions per set, load, rest between sets, and speed of the movement, was also detailed. Maximum strength training sessions involved 6-8 exercises in which 3-4 sets of 6-12 repetitions at 70-85% of the 1-repetition maximum (1RM) were performed, with 2-5 min of rest. During endurance strength training sessions, sets of 20 repetitions or maximum repetitions in 20-40s sets were performed using a load of 30-50% of 1RM, followed by < 1 min of rest. Different variants of the squat (front squat, deep back squat, Bulgarian split squat, etc.), deadlift, leg flexion and extension, and hip thrust were the most common lower limb exercises employed by the swimmers. Additionally, within 30 min after each training pool or dry-land session, a category scale (0-10) of ratings of perceived exertion (C-RPE10) (Borg et al., 1985) was undertaken to assess training intensity.

Statistical analyses

A two-way (training condition [SLT and AT] x test [pretest and postest]) repeated measures ANOVA was used to determine the differences at baseline between both training periods and the training-related effects for each dependent variable analyzed. When significant F values were obtained, pairwise differences between means were identified using Bonferroni post hoc procedures. Effect sizes (ES) using Cohen's *d* ([posttest mean – pretest mean] / pretest SD) and percentage differences ([posttest mean – pretest mean] / pretest mean × 100) were also calculated. The percentage changes after each training period were used to compare training-related effects between SLT and AT through paired samples t-tests. Significance was set at $P < 0.05$. The criteria to interpret the magnitude of the ES were as follows: <0.2 = trivial, 0.2–0.6 = small, 0.6–1.2 = moderate, 1.2–2.0 = large, and >2 = very large (Hopkins et al., 2009). All statistical tests were performed using the software package SPSS (version 20.0: SPSS, Inc., Chicago, IL, USA).

RESULTS

The results of each individual study comprising the present Doctoral Thesis are presented below. The studies are compiled in one of the three topics covered by the present Doctoral Thesis:

1. Refining the methodology of strength testing (Studies I-II)
2. Association between different strength manifestations and swimming start performance (Studies III-IV)
3. Effect of altitude training on the performance of explosive actions (Studies V-IX)

Refining the methodology of strength testing

(Studies I-II)

Study I

Predicting vertical jump height from bar velocity

Differences in the three velocities (V_{max}, FPV and $V_{take\text{-}off}$) were significant for all loads lifted (25%, 50%, 75% and 100% of BW) in both sexes ($P < 0.001$). Pairwise comparisons revealed greater V_{max} values compared with $V_{take\text{-}off}$ or FPV in all cases (Table 2). No differences were observed between FPV and $V_{take\text{-}off}$, except when women lifted loads corresponding to 75% or 100% of BW, for which $V_{take\text{-}off}$ values were significantly higher ($P < 0.05$). Greater velocities for the four loads lifted were recorded in men ($P < 0.01$).

Table 2. *Maximum velocity (V_{max}), final propulsive phase velocity (FPV) and take-off velocity ($V_{take\text{-}off}$) by load and sex.*

Sex	Variable	25% BW	50% BW	75% BW	100% BW
	V_{max} ($m \cdot s^{-1}$)	2.40 ± 0.09 [b.c]	2.09 ± 0.06 [b.c]	1.83 ± 0.05 [b.c]	1.62 ± 0.05 [b.c]
Men	**FPV ($m \cdot s^{-1}$)**	2.26 ± 0.09 [a]	1.90 ± 0.07 [a]	1.56 ± 0.06 [a]	1.25 ± 0.07 [a]
	$V_{take\text{-}off}$ ($m \cdot s^{-1}$)	2.19 ± 0.06 [a]	1.87 ± 0.05 [a]	1.61 ± 0.03 [a]	1.38 ± 0.04 [a]
	V_{max} ($m \cdot s^{-1}$)	2.02 ± 0.03 [b.c]	1.78 ± 0.03 [b.c]	1.52 ± 0.03 [b.c]	1.34 ± 0.03 [b.c]
Women	**FPV ($m \cdot s^{-1}$)**	1.85 ± 0.03 [a]	1.55 ± 0.04 [a]	1.24 ± 0.03 [a.c]	0.94 ± 0.05 [a.c]
	$V_{take\text{-}off}$ ($m \cdot s^{-1}$)	1.84 ± 0.03 [a]	1.57 ± 0.03 [a]	1.30 ± 0.03 [a.b]	1.07 ± 0.03 [a.b]

[a], Significantly different versus V_{max}. [b], Significantly different versus FPV. [c], Significantly different versus $V_{take\text{-}off}$. ($P < 0.05$).

Figure 3 depicts the regression models obtained to predict jump height from each of the two independent variables examined (V_{max} or FPV). When V_{max} was used as the independent variable, the model was able to explain 93% of the variance (F_{exp} = 1600.5, 1, 117 df), compared to 91% (F_{exp} = 1235.5, 1, 117 df) for the use of FPV as the independent variable.

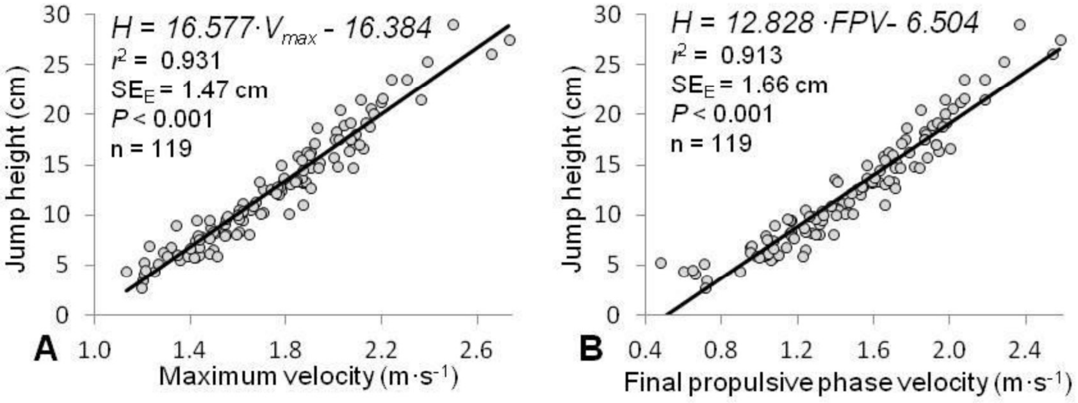

Figure 3. *Simple linear regression models used to estimate jump height. Model obtained using as the independent variable maximum velocity (A) or final propulsive phase velocity (B). H = jump height (cm);* V_{max} *= maximum velocity; FPV = final propulsive phase velocity;* SE_E *= standard error of the estimate.*

Bland–Altman plots comparing the use of the independent variables (V_{max} and FPV) to estimate jump height ($V_{take\text{-}off}$) are provided in Figure 4. The plots show that V_{max} was significantly higher than $V_{take\text{-}off}$ (t_{exp} = 25.33; 118 df; $P < 0.001$), while $V_{take\text{-}off}$ was significantly higher than FPV (t_{exp} = 4.07; 118 df; $P < 0.001$). The systematic bias ± random error was 0.22 ± 0.09 $m \cdot s^{-1}$ for V_{max} versus $V_{take\text{-}off}$ and -0.05 ± 0.12 $m \cdot s^{-1}$ for FPV versus $V_{take\text{-}off}$. As also shown in Figure 4, the differences between V_{max} and $V_{take\text{-}off}$ were homogenously distributed ($r^2 < 0.1$), while heteroscedasticity was observed for FPV ($r^2 = 0.307$).

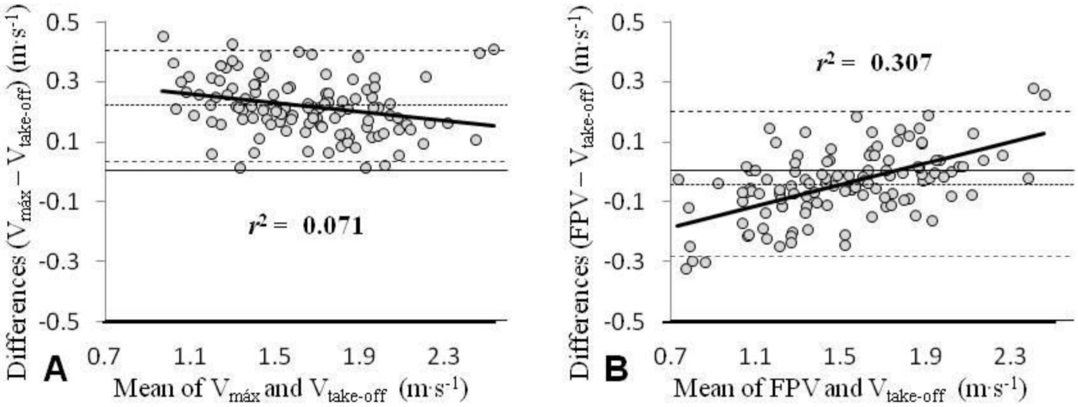

Figure 4. *Bland–Altman plots showing differences between V_{max} vs. $V_{take\text{-}off}$ (A) and FPV vs. $V_{take\text{-}off}$ (B). Each plot shows the mean difference and 95% limits of agreement (dashed lines), along with the regression line (solid line). $V_{take\text{-}off}$ = take-off velocity; V_{max} = maximum velocity; FPV = final propulsive phase velocity.*

Finally, Bland-Altman comparisons between jump height derived from the force platform data and jump height estimated from the regression models are illustrated in Figure 5. When V_{max} was used as the independent variable, 95% limits of agreement were -2.9 cm to +2.9 cm while the corresponding limits for FPV were -3.3 cm to 3.3 cm. No significant differences were detected between real jump height and height estimated using the two prediction equations (both $P > 0.99$).

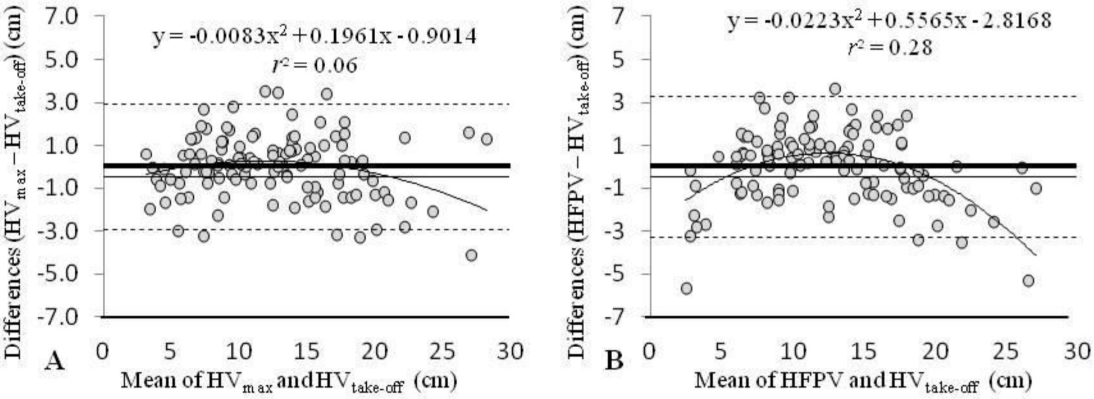

Figure 5. *Bland–Altman plots showing differences between* HV_{max} *vs.* $HV_{take\text{-}off}$ *(A) and HFPV vs.* $HV_{take\text{-}off}$ *(B). Each plot shows the mean difference and 95% limits of agreement (dashed lines), along with the regression line (solid line).* $HV_{take\text{-}off}$ *= jump height derived from take-off velocity;* HV_{max} *= jump height derived from maximum velocity; HFPV = jump height derived from final propulsive phase velocity.*

Study II

Comparison of the force-, velocity-, and power-time curves recorded with a force plate and a linear velocity transducer

Test–retest reliability for all variables collected with the force plate and the LVT are presented in Table 3.

Table 3. *Test–retest reliability for peak and mean values of force, velocity, and power collected with the force plate (FP) and the linear velocity transducer (LVT).*

		ICC (95% CI)	CV (95% CI)
Peak force	FP	0.97 (0.96–0.98)	2.2 (1.9–2.6)
	LVT	0.97 (0.96–0.98)	3.3 (2.9–4.0)
Peak velocity	FP	0.98 (0.97–0.99)	2.4 (2.0–2.8)
	LVT	0.97 (0.96–0.98)	3.0 (2.6–3.5)
Peak power	FP	0.94 (0.91–0.96)	3.4 (3.0–4.1)
	LVT	0.94 (0.91–0.96)	5.3 (4.6–6.3)
Mean force	FP	0.98 (0.97–0.99)	1.9 (1.7–2.3)
	LVT	0.97 (0.96–0.98)	3.2 (2.8–3.8)
Mean velocity	FP	0.93 (0.90–0.95)	4.6 (3.9–5.4)
	LVT	0.88 (0.82–0.92)	8.3 (7.2–9.8)
Mean power	FP	0.88 (0.82–0.92)	5.6 (4.9–6.7)
	LVT	0.86 (0.79–0.90)	10.1 (8.7–12.0)

Significant changes occurred in force, velocity, and power values when the external load was modified, as expected. Bonferroni comparisons showed higher peak force and mean force values with each increase in the external load ($P < 0.001$ for force plate and LVT), whereas peak velocity and mean velocity decreased as the load increased ($P < 0.001$ for force plate and LVT). Mean power was maximal at 25% of BW and significantly decreased with each increase in load ($p < 0.01$ for force plate and LVT). However, whereas peak power was also maximal at 25% of BW with the force plate data ($P < 0.001$), no differences were found between 25% and 50% of BW with LVT data ($P = 0.218$). Peak power at 75% and 100% of BW were significantly lower than at 25% of BW ($P < 0.001$ for force plate and LVT).

Across all four loads, the peak variables (peak force, peak velocity, and peak power) recorded by the LVT were significantly lower in comparison to the force plate data, excluding peak velocity at 25% and 50% of BW where significant differences were not found (Table 4). However, the mean variables (mean force, mean velocity and mean power) appeared to show a tendency to be higher for the LVT with the lowest loads and the opposite occurred with higher loads. As also seen in Table 4, peak variables (r = 0.94-0.99 for peak force, r = 0.83-0.91 for peak velocity and r = 0.90-0.94 for peak power) and mean variables (r = 0.96-0.99 for mean force, r = 0.87-0.89 for mean velocity and r = 0.93-0.96 for mean power) were strongly correlated between both measurement tools.

Table 4. *Impact of the load on squat jump performance.*

		External load (% body weight)			
		25%	50%	75%	100%
Peak force (N)	FP	1361.6 (148.8)	1453.6 (191.9)	1560.8 (205.9)	1691.8 (175.7)
	LVT	1312.8 (161.1)	1402.0 (186.2)	1489.5 (198.3)	1636.4 (174.1)
	% [*r*]	3.7† [0.937*]	3.7† [0.973*]	4.8† [0.976*]	3.4† [0.987*]
Peak velocity (m/s)	FP	2.027 (0.140)	1.787 (0.124)	1.586 (0.122)	1.405 (0.115)
	LVT	2.015 0.129)	1.770 (0.131)	1.522 (0.126)	1.344 (0.128)
	% [*r*]	0.6 [0.827*]	1.0 [0.909*]	4.2† [0.838*]	4.6† [0.901*]
Peak power (W)	FP	2389.1 (353.1)	2267.3 (347.0)	2193.9 (336.9)	2121.9 (275.7)
	LVT	2218.4 (349.3)	2142.7 (353.7)	2010.7 (358.1)	1965.5 (307.1)
	% [*r*]	7.7† [0.901*]	5.8† [0.938*]	9.1† [0.925*]	8.0† [0.944*]
Mean force (N)	FP	1052.6 (112.3)	1140.4 (147.1)	1226.4 (151.5)	1350.6 (141.6)
	LVT	1078.6 (132.7)	1140.8 (152.2)	1213.5 (160.3)	1318.1 (147.3)
	% [*r*]	-2.4† [0.971*]	0.0 [0.986*]	1.1† [0.989*]	2.5† [0.963*]
Mean velocity (m/s)	FP	0.919 (0.083)	0.808 (0.074)	0.705 (0.062)	0.623 (0.072)
	LVT	1.032 (0.100)	0.859 (0.103)	0.709 (0.093)	0.618 (0.089)
	% [*r*]	-10.9† [0.883*]	-6.0† [0.866*]	-0.6 [0.877*]	0.9 [0.894*]
Mean power (W)	FP	973.1 (159.8)	916.5 (159.1)	852.4 (133.0)	824.8 (126.4)
	LVT	1075.1 (199.6)	953.9 (185.9)	839.4 (172.2)	793.3 (165.1)
	% [*r*]	-9.5† [0.934*]	-3.9† [0.943*]	1.6 [0.928*]	4.0† [0.959*]

*Values are mean (SD). %, percentage of differences between FP and LVT ([FP_{mean} – LVT_{mean}] / LVT_{mean} x 100); r, Pearson's coefficient of correlation; †, Significant difference from PF ($p < 0.05$); *, Significant correlation between PF and LVT ($P \leq 0.001$).*

Changes occurred in the shape of the force-, velocity-, and power-time curves as the external load was increased (Figure 6-8). On the one hand, a steeper increase in force, velocity, and power were recorded at the beginning of the movement with the LVT data, but this difference tended to disappear as the load was increased. On the other hand, larger values in the curves were consistent for the force plate data in the final part of the repetition for all loads.

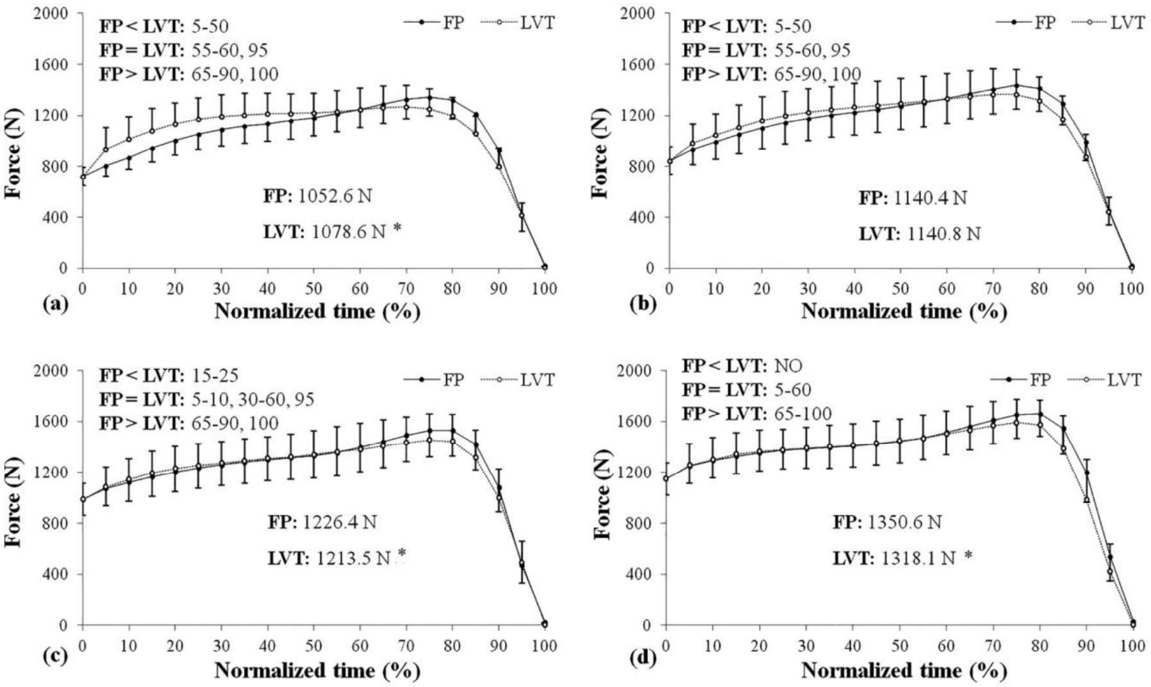

Figure 6. *Averaged force-time curves across all subjects during the squat jump at (a) 25% of body weight, (b) 50% of body weight, (c) 75% of body weight, and (d) 100% of body weight. FP < LVT, significantly greater values for LVT (p < 0.05); FP = LVT, no significant differences between measurement tools (p ≥ 0.05); FP > LVT, significantly lower values for LVT (p < 0.05). *, significant differences between FP and LVT (P < 0.05).*

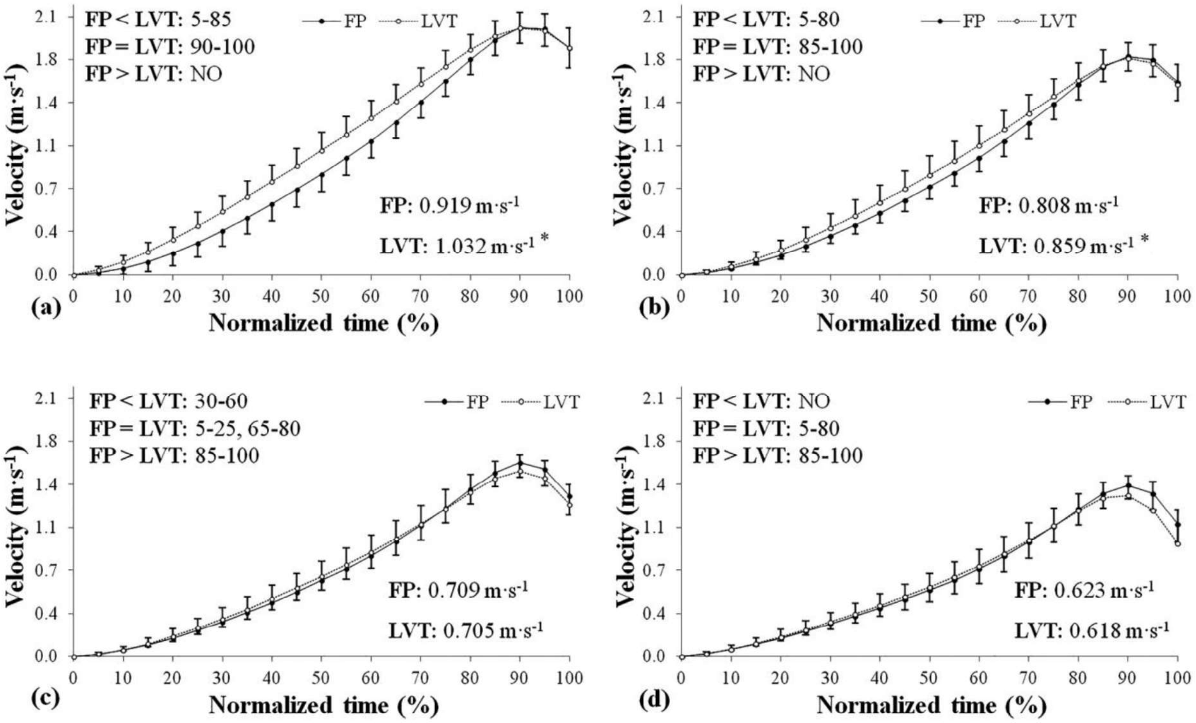

Figure 7. *Averaged velocity-time curves across all subjects during the squat jump at (a) 25% of body weight, (b) 50% of body weight, (c) 75% of body weight, and (d) 100% of body weight. FP < LVT, significantly greater values for LVT ($p < 0.05$); FP = LVT, no significant differences between measurement tools ($p \geq 0.05$); FP > LVT, significantly lower values for LVT ($p < 0.05$). *, significant differences between FP and LVT ($P < 0.05$).*

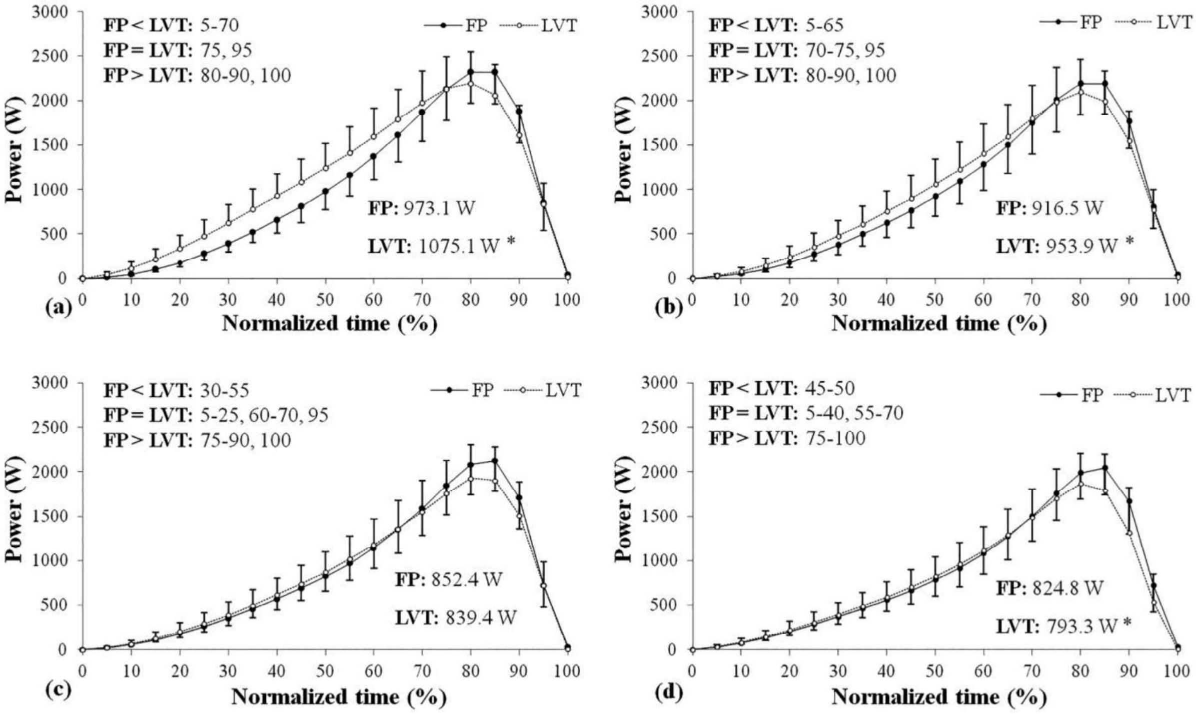

Figure 8. *Averaged power-time curves across all subjects during the squat jump at (a) 25% of body weight, (b) 50% of body weight, (c) 75% of body weight, and (d) 100% of body weight. FP < LVT, significantly greater values for LVT ($p < 0.05$); FP = LVT, no significant differences between measurement tools ($p \geq 0.05$); FP > LVT, significantly lower values for LVT ($p < 0.05$). *, significant differences between FP and LVT ($P < 0.05$).*

Association between different strength manifestations and swimming start performance

(Studies III-IV)

Study III

Relationship between different push–off variables and start performance in experienced swimmers

The descriptive data for the two starts performed are displayed in Table 5. The ES for all variables were trivial (ES < 0.2), except the time to 15 metres that was moderately lower during the freestyle start (ES = -1.02).

Table 5. *Descriptive values of the two starts performed*

Variable	Freestyle	Undulatory	*p*-value	ES
Push–off variables				
Reaction time (ms)	148.8 ± 25.6	145.6 ± 27.7	0.642	0.119
Movement time (ms)	614.1 ± 46.6	618.8 ± 51.6	0.498	-0.096
Push–off time (ms)	762.9 ± 57.4	764.4 ± 56.4	0.481	-0.028
Take–off angle (º)	-0.40 ± 7.73	-1.25 ± 7.52	0.019	0.112
Average horizontal force (N)	385.3 ± 48.8	377.6 ± 48.6	0.028	0.159
Average vertical force (N)	566.5 ± 77.3	567.5 ± 77.2	0.016	-0.014
Peak horizontal force (N)	619.4 ± 87.4	619.8 ± 97.4	0.959	-0.004
Peak vertical force (N)	850.4 ± 167.9	846.4 ± 173.4	0.813	0.023
Horizontal impulse (N·s)	231.0 ± 28.2	229.7 ± 27.9	0.331	0.043
Vertical impulse (N·s)	346.4 ± 77.4	340.3 ± 80.8	0.302	0.077
Resultant impulse (N·s)	417.6 ± 75.4	412.0 ± 78.0	0.281	0.072

Horizontal take–off velocity (m·s^{-1})	4.00 ± 0.30	3.98 ± 0.30	0.320	0.069
Vertical take–off velocity (m·s^{-1})	-0.05 ± 0.54	-0.11 ± 0.52	0.013	0.115
Resultant take–off velocity (m·s^{-1})	4.03 ± 0.30	4.01 ± 0.30	0.296	0.071
Average horizontal acceleration (m·s^{-2})	6.70 ± 0.75	6.56 ± 0.75	0.029	0.182
Average vertical acceleration (m·s^{-2})	-0.09 ± 0.89	-0.20 ± 0.88	0.016	0.122
Peak horizontal acceleration (m·s^{-2})	10.77 ± 1.46	10.75 ± 1.47	0.905	0.010
Peak vertical acceleration (m·s^{-2})	4.83 ± 2.03	4.74 ± 1.99	0.762	0.044
Time analysis				
Time to 5 m (s)	1.77 ± 0.12	1.76 ± 0.13	0.118	0.123
Time to 10 m (s)	4.81 ± 0.25	4.83 ± 0.29	0.448	-0.096
Time to 15 m (s)	8.07 ± 0.39	8.56 ± 0.57	< 0.001	-1.021

ES, effect size (freestyle mean – undulatory mean / SD_{both}). Vertical forces represent only the dynamic component of total vertical force (body weight subtracted).

Pearson's product–moment correlations values between the push–off variables and times to 5, 10 and 15 metres during the freestyle and undulatory starts are depicted in Table 6. Only three variables were significantly correlated ($P < 0.05$) with all times measured in the two starts performed: average horizontal acceleration (freestyle: r = -0.58 to -0.71; and undulatory: r = -0.55 to -0.66), horizontal take–off velocity (freestyle: r = -0.56 to -0.69; and undulatory: r = -0.53 to -0.67) and resultant take–off velocity (freestyle: r = -0.53 to -0.65; and undulatory: r = -0.52 to -0.61).

Table 6. *Pearson's product–moment correlation values between push–off variables and time parameters*

	Freestyle			Undulatory		
	T5	T10	T15	T5	T10	T15
Reaction time (ms)	0.30	0.04	0.14	0.41	0.13	0.02
Movement time (ms)	0.54*	0.37	0.36	0.38	0.31	0.37
Push–off time (ms)	0.57**	0.32	0.35	0.52*	0.41	0.34
Take–off angle (º)	-0.04	-0.01	0.00	0.05	-0.02	0.17
Average horizontal force (N)	-0.58**	-0.70**	-0.62**	-0.39	-0.55*	-0.36
Average vertical force (N)	-0.07	-0.03	-0.04	0.00	-0.03	0.14
Peak horizontal force (N)	-0.20	-0.30	-0.22	-0.08	-0.32	0-.32
Peak vertical force (N)	0.03	-0.11	-0.11	0.18	-0.02	0.12
Horizontal impulse (N·s)	-0.32	-0.52*	-0.43	-0.18	-0.40	-0.16
Vertical impulse (N·s)	0.27	0.14	0.15	0.35	0.13	0.33
Resultant impulse (N·s)	0.18	0.03	0.05	0.29	0.05	0.28
Horizontal take–off velocity ($m·s^{-1}$)	-0.65**	-0.69**	-0.56**	-0.67**	-0.58**	-0.53*
Vertical take–off velocity ($m·s^{-1}$)	-0.07	-0.04	-0.03	0.02	-0.04	0.14
Resultant take–off velocity ($m·s^{-1}$)	-0.61**	-0.65**	-0.53*	-0.61**	-0.53*	-0.52*
Average horizontal acceleration ($m·s^{-2}$)	-0.71**	-0.65**	-0.58**	-0.66**	-0.57**	-0.55*
Average vertical acceleration ($m·s^{-2}$)	-0.09	-0.07	-0.06	-0.01	-0.06	0.12
Peak horizontal acceleration ($m·s^{-2}$)	-0.27	-0.22	-0.14	-0.27	-0.33	-0.50*
Peak vertical acceleration ($m·s^{-2}$)	-0.09	-0.14	-0.13	0.02	-0.04	-0.03

*T5, time to 5 m; T10, time to 10 m; T15, time to 15 m. Significant correlations: * $P < 0.05$, ** $P < 0.01$.*

Finally, the best MLR models obtained to predict the performance (time to 5, 10 and 15 m) in the freestyle (Table 7) and undulatory starts (Table 8) by using the push–off variables not dependent to body mass as independent variables are also displayed. The variance explained by the MLR models tended to diminish with increasing distances in both freestyle start and undulatory start. The correlations between horizontal take–off velocity and average horizontal acceleration, which were the two main predictor variables, were very large in both freestyle start (r = 0.79; P < 0.001) and undulatory start (r = 0.76; P < 0.001). In addition, the correlation between vertical take–off velocity and average vertical acceleration in both starts was perfect (r = 1; P < 0.001).

Table 7. *Parameters of the explanatory multiple linear regression models generated with times to 5, 10 and 15 m as the predicted variables during the freestyle start*

	Predicted variables		
	T5	T10	T15
Constant (a)	2.595 **	7.706 **	9.953 **
Average horizontal acceleration ($m \cdot s^{-2}$)	-0.208 (-1.285) **	Excluded	-0.617 (-1.130) **
Peak horizontal acceleration ($m \cdot s^{-2}$)	0.052 (0.629) **	Excluded	0.203 (0.723) **
Average vertical acceleration ($m \cdot s^{-2}$)	-0.043 (-0.310) *	-0.128 (-0.450) *	Excluded
Horizontal take–off velocity ($m \cdot s^{-1}$)	Excluded	-0.727 (-0.878) **	Excluded
Push–off time (s)	Excluded	Excluded	Excluded
Vertical take–off velocity ($m \cdot s^{-1}$)	Excluded	Excluded	Excluded
***Adj. r^2* (SE$_E$)**	**0.735 (0.063)**	**0.593 (0.161)**	**0.503 (0.290)**
ANOVA *p*-value	**[< 0.001]**	**[< 0.001]**	**[0.001]**

Data are MLR model raw-score constants (a), raw-score (b), and standardized coefficients (β-weights, in parenthesis). Predicted variables are: T5, time to 5 m; T10, time to 10 m; T15, *time to 15 m. Adj. r^2, adjusted Pearson's multivariate coefficient of determination; SE_E, standard error of the estimate (sec); coefficient significance (* $P < 0.05$, ** $P < 0.01$). Excluded: a variable not entering the stepwise regression MLR model.*

Table 8. *Parameters of the explanatory multiple linear regression models generated with times to 5, 10 and 15 meters as the predicted variables during the undulatory start.*

	Predicted variables		
	T5	T10	T15
Constant (a)	2.460 **	7.846 **	11.290 **
Average horizontal acceleration ($m \cdot s^{-2}$)	Excluded	Excluded	-0.421 (-0.552) *
Peak horizontal acceleration ($m \cdot s^{-2}$)	Excluded	Excluded	Excluded
Average vertical acceleration ($m \cdot s^{-2}$)	-0.057 (-0.384) *	Excluded	Excluded
Horizontal take–off velocity ($m \cdot s^{-1}$)	-0.332 (-0.763) **	-0.763 (-0.800) **	Excluded
Push–off time (s)	0.786 (0.340) *	Excluded	Excluded
Vertical take–off velocity ($m \cdot s^{-1}$)	Excluded	-0.241 (-0.441) *	Excluded
***Adj. r^2* (SE_E)**	**0.632 (0.079)**	**0.425 (0.217)**	**0.263 (0.489)**
ANOVA *p*-value	**[< 0.001]**	**[0.003]**	**[0.014]**

Data are MLR model raw-score constants (a), raw-score (b), and standardized coefficients (β-weights, in parenthesis). Predicted variables are: T5, time to 5 m; T10, time to 10 m; T15, time to 15 m. Adj. r^2, adjusted Pearson's multivariate coefficient of determination; SE_E, standard error of the estimate (sec); coefficient significance ($p < 0.05$, ** $p < 0.01$). Excluded: a variable not entering the stepwise regression MLR model.*

Study IV

The relationship between the lower-body muscular profile and swimming start performance

The average swim start times were 1.77 ± 0.12 s, 4.83 ± 0.23 s and 8.10 ± 0.37 s at 5 (T5), 10 (T10) and 15 (T15) m, respectively.

Large correlations between the SJ's and CMJ's take-off velocity (TOV) and T5 were found, while only a moderate correlation between CMJ's TOV and T10 was obtained (Table 9). No correlations between the TOV and T15 were found. Similar results were obtained for peak power normalized per kg of body mass, while other variables (peak power, peak force, and peak force normalized per kg of body mass) showed no significant correlations.

Table 9. *Pearson's correlation coefficient between the squat and countermovement jumps and times to 5, 10, and 15 m.*

Jump	Variable	Mean ± SD	T5	T10	T15
SJ	PF (N)	1273.1 ± 191.5	0.01	-0.03	-0.14
	PF_{rel} ($N \cdot kg^{-1}$)	21.59 ± 2.80	-0.06	0.02	-0.12
	PP (W)	2728.5 ± 361.7	-0.40	-0.39	-0.23
	PP_{rel} ($W \cdot kg^{-1}$)	46.24 ± 4.97	-0.57**	-0.42	-0.28
	TOV ($m \cdot s^{-1}$)	2.216 ± 0.15	-0.56*	-0.34	-0.23
CMJ	PF (N)	1403.3 ± 176.4	-0.02	-0.14	-0.12
	PF_{rel} ($N \cdot kg^{-1}$)	23.72 ± 1.46	-0.19	-0.17	-0.17
	PP (W)	2676.7 ± 384.3	-0.37	-0.43	-0.34
	PP_{rel} ($W \cdot kg^{-1}$)	45.27 ± 4.73	-0.61**	-0.55*	-0.43
	TOV ($m \cdot s^{-1}$)	2.344 ± 0.17	-0.62**	-0.49*	-0.36

*SJ, squat jump; CMJ; countermovement jump; PF, peak force; PF_{rel}, peak force normalize to body mass; PP, peak power; PP_{rel}, peak power normalize to body mass; TOV, take-off velocity; T5, time to 5 m; T10, time to 10 m; T15, time to 15 m; Significant correlations: * $p < 0.05$, ** $p < 0.01$.*

The peak velocity reached during the jumps with additional weights was the variable most related with swimming start performance (Table 10). Generally, Pearson's product–moment correlations coefficient ranged from large to very large in the four loads used (r = -0.57 to -0.66 at 25%BW; r = -0.57 to -0.72 at 50%BW; r = -0.59 to -0.68 at 75%BW; r = -0.50 to -0.64 at 100%BW).

Table 10. *Pearson's correlation coefficient between the squat jumps with additional weights and times to 5, 10, and 15 m.*

Load	Variable	Mean ± SD	T5	T10	T15
	PF (N)	1346.8 ± 157.5	-0.03	-0.20	-0.16
	PF_{rel} ($N·kg^{-1}$)	23.7 ± 1.9	-0.20	-0.25	-0.22
25% BW	PP (W)	2232.7 ± 315.3	-0.44	-0.49*	-0.49*
	PP_{rel} ($W·kg^{-1}$)	39.3 ± 4.4	-0.62**	-0.55*	-0.57**
	BV ($m·s^{-1}$)	2.016 ± 0.15	-0.66**	-0.57**	-0.63**
	PF (N)	1408.7 ± 182.2	-0.02	-0.15	-0.13
	PF_{rel} ($N·kg^{-1}$)	24.7 ± 1.4	-0.28	-0.34	-0.31
50% BW	PP (W)	2168.9 ± 327.1	-0.41	-0.42	-0.43
	PP_{rel} ($W·kg^{-1}$)	38.1 ± 4.2	-0.63**	-0.51*	-0.54*
	BV ($m·s^{-1}$)	1.784 ± 0.14	-0.72**	-0.57**	-0.63**
	PF (N)	1497.6 ± 186.5	-0.01	-0.13	-0.12
	PF_{rel} ($N·kg^{-1}$)	26.2 ± 1.0	-0.38	-0.42	-0.43
75% BW	PP (W)	2040.4 ± 312.5	-0.31	-0.38	-0.43
	PP_{rel} ($W·kg^{-1}$)	35.7 ± 3.5	-0.57**	-0.54*	-0.64**
	BV ($m·s^{-1}$)	1.539 ± 0.11	-0.63**	-0.59**	-0.68**
	PF (N)	1632.9 ± 184.1	0.04	0.03	-0.08
	PF_{rel} ($N·kg^{-1}$)	28.2 ± 1.1	-0.25	-0.22	-0.39
100% BW	PP (W)	1978.4 ± 289.4	-0.33	-0.29	-0.45
	PP_{rel} ($W·kg^{-1}$)	34.2 ± 3.6	-0.54*	-0.47*	-0.64**
	BV ($m·s^{-1}$)	1.352 ± 0.11	-0.57*	-0.50*	-0.64**

*PF, peak force; PF_{rel}, peak force normalize to body mass; PP, peak power; PP_{rel}, peak power normalize to body mass; BV, peak velocity. T5, time to 5 m; T10, time to 10 m; T15, time to 15 m; BW, body weight; Significant correlations: * $P < 0.05$, ** $P < 0.01$.*

In contrast, there were no correlations between measured parameters of progressive and explosive maximal isometric knee contractions (i. e., extension and flexion) and swimming start performance (Table 11).

Table 11. *Pearson's correlation coefficient between the leg extension and leg flexion maximal voluntary isometric contractions and times to 5, 10, and 15 m.*

Variable	Mean ± SD	T5	T10	T15
Maximum torque leg extension (N·m)	165.8 ± 17.4	-0.24	-0.16	-0.15
Relative maximum torque leg extension ($N{\cdot}m{\cdot}kg^{-1}$)	2.937 ± 0.42	-0.28	-0.11	-0.13
Maximum torque leg flexion (N·m)	75.0 ± 16.3	-0.23	-0.20	-0.18
Relative Maximum torque leg flexion ($N{\cdot}m{\cdot}kg^{-1}$)	1.310 ± 0.21	-0.38	-0.25	-0.23
Explosive torque leg extension (N·m)	12.6 ± 3.3	-0.19	-0.21	-0.13
Relative Explosive torque leg extension ($N{\cdot}m{\cdot}kg^{-1}$)	0.224 ± 0.06	-0.20	-0.18	-0.11
Explosive torque leg flexion (N·m)	5.1 ± 1.7	-0.20	-0.19	-0.02
Relative Explosive torque leg flexion ($N{\cdot}m{\cdot}kg^{-1}$)	0.089 ± 0.03	-0.25	-0.19	-0.04

T5, time to 5 m; T10, time to 10 m; T15, time to 15 m.

Effect of altitude training on the performance of explosive actions

(Papers V-IX)

Study V

Effect of acute exposure to moderate altitude on muscle power: hypobaric hypoxia vs normobaric hypoxia

Intragroup comparisons revealed a moderate increment in 1RM (+5.73%; ES = 0.3) and a small increase in the overall load corresponding to P_{max} (+3.29%; ES = 0.2) compared to normoxia values in G1 attributable to the subjects' ascent to a moderate altitude, whereas no differences were detected in G2 (Table 12). When the effect of two hypoxia conditions were compared (effect of G1 vs effect of G2), natural hypoxia only was linked to a higher RM (P = 0.01; ES = 1.1) together a moderate increase to the load corresponding to P_{max} near to signification (P = 0.09, ES = 0.69).

Table 12. *Intra group comparisons of results linked to maximum power and maximum dynamic force.*

	1RM (kg)			P_{max} ($W \cdot kg^{-1}$)			$LoadP_{max}$ (kg)			$\%RMP_{max}$		
	G1	G2	*P*	G1	G2	*P*	G1	G2	*P*	G1	G2	*P*
N	82.4 ± 14.8	76.4 ± 16.3	0.324	5.29 ± 0.60	4.87 ± 0.51	0.074	48.3 ± 8.0	43.1 ± 8.6	0.128	58.3 ± 4.2	56.8 ± 5.3	0.442
H	86.5 ± 16.2	75.5 ± 18.6	0.109	5.36 ± 0.64	4.82 ± 0.47	*0.025*	49.7 ± 8.2	42.6 ± 8.7	*0.044*	56.9 ± 4.3	57.4 ± 5.9	0.803
P	*0.004*	0.588	-----	0.244	0.402	-----	*0.040*	0.631	------	0.355	0.765	-----

1RM= 1 repetition maxium; P_{max}= Maximum power; $LoadP_{max}$= Absolute load linked to maximum power; $\%RMP_{max}$= Percentage of 1RM linked to maximum power; N= Conditions of normoxia; H= Conditions of hypoxia; G1= Group 1; G2= Group 2; P= p-value.

Tables 13 and 14 provide the values of P_{mean}, P_{peak} and V_{mean} for the different loads in G1 and G2 respectively. Comparisons of HH vs. N1 revealed significant increases at HH in P_{mean}, P_{peak} and V_{mean} from 60 kg, except in the P_{peak} at 80 kg in which the significance was border liner ($P < 0.08$). In contrast, the same comparison in G2 indicated no significant differences for any of the loads examined.

Table 13. *Mean power, peak power and mean velocity recorded in conditions of normoxia versus hypobaric hypoxia.*

			P_{mean} (W·kg^{-1})		P_{peak} (W·kg^{-1})		V_{mean} (m·s^{-1})	
Load (kg)	n	Con	Mean ± SD	*P*	Mean ± SD	*P*	Mean ± SD	*P*
20	17	N	3.82 ± 0.51	0.882	10.10 ± 1.26	0.289	1.387 ±0.11	0.810
		HH	3.83 ± 0.46		10.27 ± 1.09		1.393 ± 0.14	
30	17	N	4.63 ± 0.56	0.895	10.25 ± 1.21	0.003	1.160 ± 0.13	0.776
		HH	4.64 ± 0.50		10.88 ± 1.15		1.165 ± 0.12	
40	17	N	5.15 ± 0.52	0.082	10.86 ± 1.37	0.984	0.994 ± 0.13	0.089
		HH	5.03 ± 0.51		10.86 ± 1.36		0.972 ± 0.13	
50	17	N	5.01 ± 0.68	0.263	10.38 ± 1.56	0.894	0.791 ± 0.17	0.357
		HH	5.14 ± 0.69		10.34 ± 1.25		0.806 ± 0.15	
60	17	N	4.57 ± 1.08	0.004	9.04 ± 1.72	0.016	0.613 ±0.19	0.010
		HH	4.82 ± 1.02		9.55 ± 1.26		0.641 ± 0.18	
70	13	N	4.54 ± 1.16	0.041	8.73 ± 1.42	0.051	0.524 ± 0.17	0.048
		HH	4.77 ± 1.16		9.31 ± 1.74		0.548 ± 0.17	
80	11	N	3.82 ± 1.29	0.001	7.64 ± 1.72	0.076	0.413 ± 0.16	0.001
		HH	4.20 ± 1.25		8.30 ± 1.46		0.452 ± 0.16	
90	7	N	3.65 ± 0.71	0.025	6.91 ± 0.82	0.049	0.357 ± 0.09	0.024
		HH	3.93 ± 0.82		7.62 ± 0.62		0.384 ± 0.09	
100	5	N	2.83 ± 0.89	0.210	6.09 ± 0.66	0.552	0.254 ± 0.08	0.193
		HH	3.23 ± 0.53		6.29 ± 0.73		0.286 ± 0.04	

P_{mean}= Mean power; P_{peak}= Peak power; V_{mean}= Mean velocity; n= Number of values included in the analysis; Cond= Test conditions; N= Normoxia; HH= Hypobaric hypoxia.

Table 14. *Mean power, peak power and mean velocity recorded in conditions of normoxia versus normobaric hypoxia.*

			P_{mean} (W·kg^{-1})		P_{peak} (W·kg^{-1})		V_{mean} (m·s^{-1})	
Load	n	Con	Mean ± SD	*P*	Mean ± SD	*P*	Mean ± SD	*P*
20	11	N	3.69 ± 0.27	0.595	8.81± 0.93	0.959	1.249 ± 0.14	0.669
		NH	3.75 ± 0.47		8.79± 1.00		1.263 ± 0.13	
30	11	N	4.47 ± 0.27	0.807	8.96± 0.90	0.414	1.045 ± 0.14	0.673
		NH	4.45 ± 0.44		9.16±0.94		1.038 ± 0.13	
40	11	N	4.67 ± 0.48	0.768	8.58± 1.41	0.498	0.840 ± 0.17	0.487
		NH	4.63 ± 0.47		9.01±1.99		0.829 ± 0.16	
50	11	N	4.46 ± 0.77	0.989	7.91± 1.48	0.627	0.654 ± 0.17	0.986
		NH	4.46 ± 0.85		7.79± 1.74		0.655 ± 0.18	
60	9	N	4.32 ± 1.28	0.889	7.67± 1.96	0.643	0.553 ± 0.19	0.804
		NH	4.29 ± 0.76		7.49± 1.71		0.546 ± 0.15	
70	7	N	4.04 ± 1.10	0.605	7.41± 1.11	0.658	0.456 ± 0.13	0.704
		NH	3.97 ± 1.08		7.33± 1.02		0.451 ± 0.13	
80	6	N	3.08 ± 1.37	0.152	6.20± 1.69	0.839	0.312 ± 0.15	0.153
		NH	3.30 ± 1.28		6.22± 1.52		0.336 ± 0.15	
90	3	N	3.25 ± 0.96	0.591	6.75 ± 0.36	0.541	0.292 ± 0.10	0.758
		NH	2.87 ± 1.65		6.14 ± 1.77		0.272 ± 0.20	
100	2	N	2.32 ± 0.00	0.242	4.24 ± 0.39	0.268	0.198 ± 0.06	0.323
		NH	2.90 ± 0.33		5.18 ± 0.98		0.252 ± 0.10	

P_{mean}= Mean power; P_{peak}= Peak power; V_{mean}= Mean velocity; n= Number of values included in the analysis; Cond= Test conditions; N= Normoxia; NH= Normobaric hypoxia.

Study VI

Relationship between vertical jump height and swimming start performance before and after an altitude training camp.

The two-way repeated measures ANOVA conducted in the present study to compare squat jump height revealed significant main effects for test (F[1,14] = 23.1, $P < 0.001$, $\eta_p^2 = 0.622$) and load (F[1.6,22.0] = 765.9, $P < 0.001$, $\eta_p^2 = 0.982$). The interaction between test and load did not reach statistical significance (F[4,56] = 1.826, $P = 0.137$, $\eta_p^2 = 0.115$). A significant increase in squat jump height after the altitude training period was observed (Table 15). The highest squat jump height was obtained without additional load, and significantly decreased with each subsequent increase in load ($P < 0.001$ in all comparisons).

Table 15. *Comparison of vertical jump height with the different additional loads lifted before and after the training period.*

Load (% body weight)	Pretest (cm)	Postest (cm)	*P*-value	Absolute difference (cm) (95% CI)	Percent difference (%) (95% CI)	Effect size
0%	28.8 ± 3.9	30.7 ± 3.5	0.001	1.8 (0.9–2.8)	6.4 (3.0–9.8)	0.47
25%	20.9 ± 3.2	22.0 ± 2.8	0.010	1.1 (0.3–1.9)	5.4 (1.5–9.2)	0.35
50%	15.1 ± 2.6	16.4 ± 2.6	<0.001	1.2 (0.7–1.8)	8.2 (4.6–11.8)	0.48
75%	10.7 ± 2.1	11.7 ± 2.3	0.026	1.0 (0.1–1.8)	9.1 (1.3–17.0)	0.47
100%	7.0 ± 2.1	7.8 ± 2.4	0.018	0.8 (0.2–1.4)	11.2 (2.3–20.2)	0.38
Overall	16.5 ± 2.5	17.7 ± 2.5	<0.001	1.2 (0.7–1.7)	7.2 (4.0–10.5)	0.47

Overall, data obtained averaging the five loads; P, statistical significance; CI, 95% confidence interval. Effect size, (postest mean – pretest mean)/$SD_{pretest}$.

The two-way repeated measures ANOVA conducted in the present study to examine swimming start performance revealed significant main effects for test (F[1,14] = 19.9, $P < 0.001$, $\eta_p^2 = 0.587$) and distance (F[1.1,15.1] = 2800.5, $P < 0.001$, $\eta_p^2 = 0.995$). The interaction between test and distance also reached statistical significance (F[1.3,17.9] = 11.2, $P = 0.001$, $\eta_p^2 = 0.444$). A significant increase in swimming start performance after the altitude training period was observed (Table 16).

Table 16. *Comparison of swimming start performance before and after the training period.*

	Pretest (s)	Postest (s)	*P*-value	Absolute difference (s) (95% CI)	Percent difference (%) (95% CI)	Effect size
Time to 5 m	1.58 ± 0.09	1.54 ± 0.09	0.002	0.042 (0.02–0.07)	2.7 (1.2–4.2)	0.49
Time to 10 m	4.08 ± 0.21	3.97 ± 0.22	0.002	0.109 (0.05–0.17)	2.7 (1.1–4.2)	0.52
Time to 15 m	7.30 ± 0.46	7.07 ± 0.44	0.001	0.224 (0.11–0.34)	3.1 (1.5–4.7)	0.48

P, statistical significance; CI, 95% confidence interval. Effect size, (postest mean – pretest mean)/$SD_{pretest}$.

Pearson's product–moment correlations values between the squat jump height reached in the different jumps and the time to 5, 10, and 15 meters in the pretest and postest are illustrated in Table 17. Most of the correlations ranged between large (0.5–0.69) and very large (0.7–0.89). As an example, the relationship between the overall jump height and the time to 10 meters in pretest and postest are shown in Figure 9.

Table 17. *Relationship between vertical jump height and swimming start performance before and after the altitude training period.*

	Pretest			Postest		
	T5	T10	T15	T5	T10	T15
0% body weight	-0.55*	-0.77**	-0.67**	-0.50	-0.71**	-0.58*
25% body weight	-0.52*	-0.68**	-0.58*	-0.41	-0.63*	-0.50
50% body weight	-0.53*	-0.65**	-0.51	-0.58*	-0.74**	-0.60*
75% body weight	-0.47	-0.73**	-0.72**	-0.39	-0.58**	-0.57*
100% body weight	-0.46	-0.68**	-0.72**	-0.43	-0.61*	-0.57*
Overall	-0.56*	-0.77**	-0.70**	-0.50	-0.71**	-0.61*

*Overall, data obtained averaging the five loads; T5, time to 5 m; T10, time to 10 m; T15, time to 15 m. Significant correlations: * P < 0.05, ** P < 0.01.*

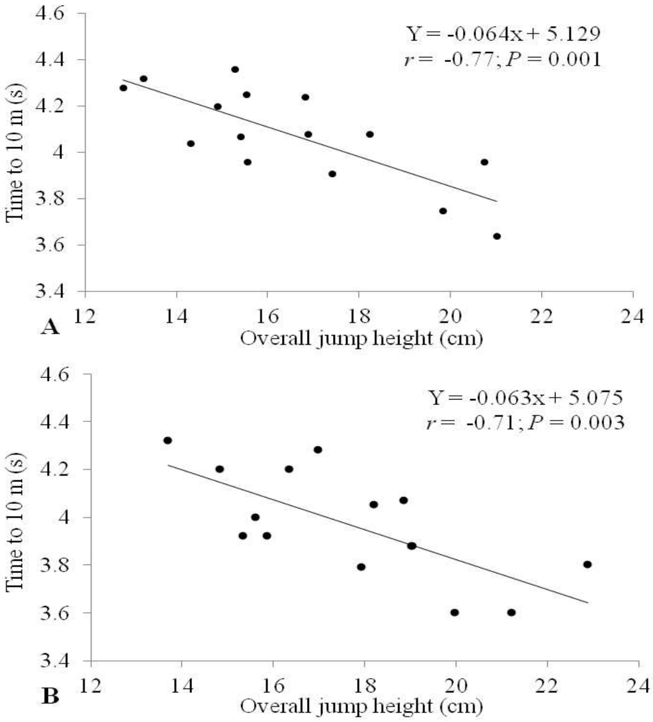

Figure 9. *Relationship between the overall jump height and the time to 10 meters in pretest (A) and postest (B).*

Pearson's product–moment correlation values between the changes in squat jump height and the changes in swimming start performance (time to 5, 10, and 15 meters) following the altitude training period is shown in Table 18. The percentage increment in squat jump height observed after the training period was inversely related to swimming start time (higher increment in jump height = greater reduction in start time). As an example, the relationship between the change in overall jump height and the change in the time to 10 meters is shown in Figure 10.

Table 18. *Relationship between the changes in vertical jump height and the change in swimming start performance following the altitude training camp.*

	T5	T10	T15
0% body weight	-0.53*	-0.55*	-0.45
25% body weight	-0.36	-0.34	-0.43
50% body weight	-0.59*	-0.47	-0.31
75% body weight	0.04	-0.67**	-0.50
100% body weight	-0.24	-0.63*	-0.57*
Overall	-0.47	-0.73**	-0.62*

*Overall, data obtained averaging the five loads; T5, time to 5 m; T10, time to 10 m; T15, time to 15 m. Significant correlations: * $P < 0.05$, ** $P < 0.01$.*

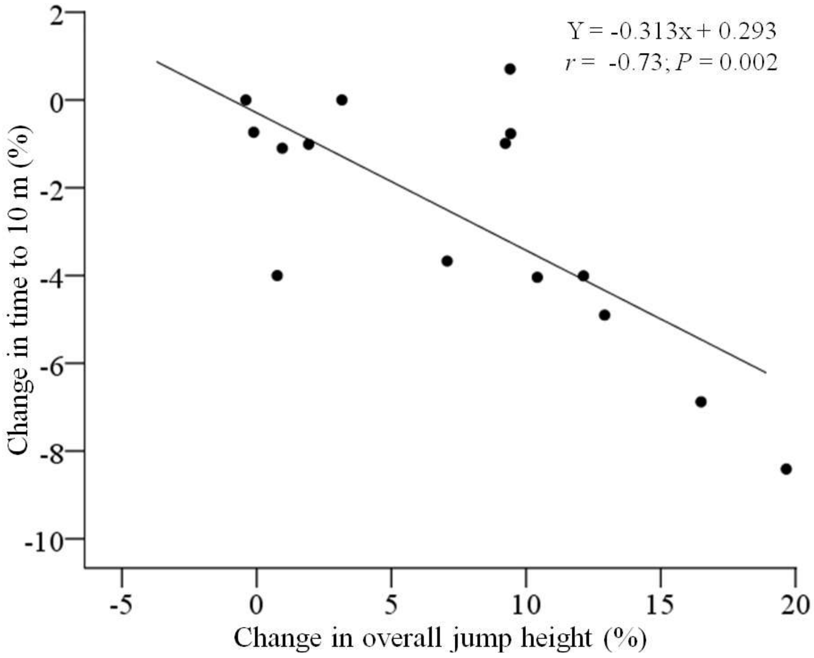

Figure 10. *Relationship between the change in overall jump height and the change in the time to 10 meters after the altitude training period.*

Study VII

The effect of acute and chronic exposure to hypobaric hypoxia on loaded squat jump performance

The three-way repeated measures ANOVA revealed significant main effects for test (F[1,15] = 33.6, $P < 0.001$, $\eta_p^2 = 0.691$), condition (F[1,15] = 135.1, $P < 0.001$, $\eta_p^2 = 0.900$) and load (F[1.4,21.7] = 1888.6, $P < 0.001$, $\eta_p^2 = 0.991$). However, neither of the interactions reached statistical significance: test x condition (F[1,15] = 2.32, $P = 0.149$, $\eta_p^2 = 0.134$), test x load (F[3,45] = 1.99, $P = 0.129$, $\eta_p^2 = 0.117$), condition x load (F[3,45] = 1.27, $P = 0.296$, $\eta_p^2 = 0.078$) and test x condition x load (F[3,45] = 0.06, $P = 0.983$, $\eta_p^2 = 0.004$).

Table 19 summarizes peak velocity descriptive values for all conditions tested in the present study. An overall increase in the load-velocity relationship of 3.1% (95% CI = 1.9–4.2%) in the postest (2.128 ± 0.115 $\text{m}\cdot\text{s}^{-1}$) compared to the pretest (2.065 ± 0.126 $\text{m}\cdot\text{s}^{-1}$) was observed ($P < 0.001$). A 5.5% (95% CI = 4.5–6.5%) increase in peak velocity during the test conducted in hypoxia (2.153 ± 0.120 $\text{m}\cdot\text{s}^{-1}$) compared to normoxia (2.041 ± 0.120 $\text{m}\cdot\text{s}^{-1}$) was reached ($P < 0.001$).

Table 19. *Peak velocity values ($m\cdot s^{-1}$) for the different conditions tested*

Load	Pretest		Postest	
(% body weight)	Normoxia	Hypoxia	Normoxia	Hypoxia
25%	2.463 ± 0.17	2.570 ± 0.17	2.539 ± 0.12	2.615 ± 0.15
50%	2.104 ± 0.16	2.237 ± 0.13	2.205 ± 0.13	2.295 ± 0.14
75%	1.843 ± 0.13	1.985 ± 0.13	1.908 ± 0.12	2.012 ± 0.11
100%	1.591 ± 0.11	1.728 ± 0.11	1.673 ± 0.10	1.781 ± 0.09

Normoxia 1 vs. Hypoxia 1 // Normoxia 2 vs. Hypoxia 2

Higher peak velocity values were reached during the tests conducted in hypoxia in both pretest and postest with the four loads analyzed (Figure 11). An overall increase in peak velocity during the test performed in hypoxia of 6.5% in pretest (95% CI = 4.7–8.2%, $P < 0.001$, ES = 0.98) and 4.5% in postest (95% CI = 3.2–5.9%, $P < 0.001$, ES = 0.81) was observed. All swimmers, apart from subject 8 in the pretest (N1 = 1.948 $m\cdot s^{-1}$ and H1 = 1.941 $m\cdot s^{-1}$) and subject 3 in the postest (N2 = 2.108 $m\cdot s^{-1}$ and H2 = 2.086 $m\cdot s^{-1}$), showed higher peak velocity values during the tests conducted in hypoxia (Figure 11).

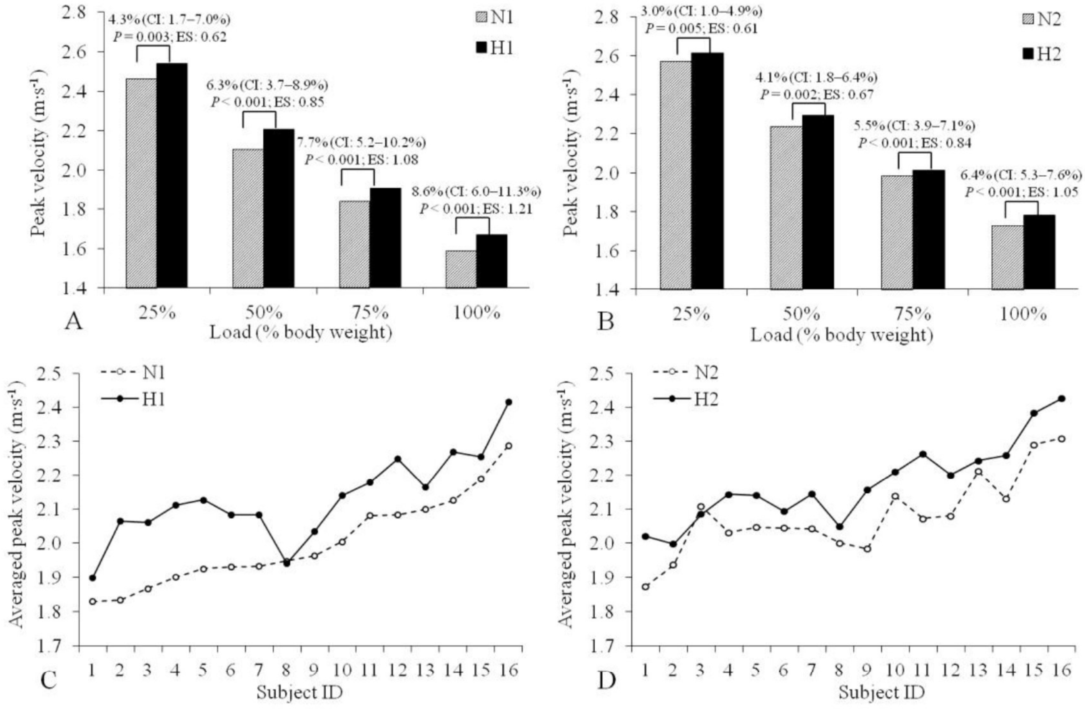

Figure 11. *Effect of altitude exposure on peak bar velocity during the loaded squat jump in pretest (A and C) and postest (B and D). Graphs A and B show the comparison of mean values with the four loads used. Graphs C and D show individual responses using the average peak velocity value of the four loads. N1, pretest conducted in normoxia; H1, pretest conducted in hypoxia; N2, postest conducted in normoxia; H2, postest conducted in hypoxia; CI, 95% confidence interval; P, statistical significance; ES, effect size ([mean hypoxia – mean normoxia] / SD normoxia).*

Normoxia 1 vs. Normoxia 2 // Hypoxia 1 vs. Hypoxia 2

Significant increases in peak velocity were observed after the training period with the four loads analyzed (Figure 12). An overall increment of 4.0% (95% CI = 2.3–5.8%, $P < 0.001$, ES = 0.61) considering the data for normoxia tests and 2.1% (95% CI = 0.6–3.7%, $P = 0.008$, ES = 0.36) considering the data for hypoxia tests was achieved. Analysis of the data recorded in normoxia, showed that 75% of the swimmers (n = 12) improved PV performance by more than 1%, whereas the changes in the remaining 25% (n = 4) were between +1% and

-1%. Considering the data recorded in hypoxia, 62.5% of the swimmers (n = 10) improved peak velocity performance by more than 1%, 25% (n = 4) were between +1% and -1%, and 12.5% (n = 2) showed a reduction in peak velocity performance by more than 1%.

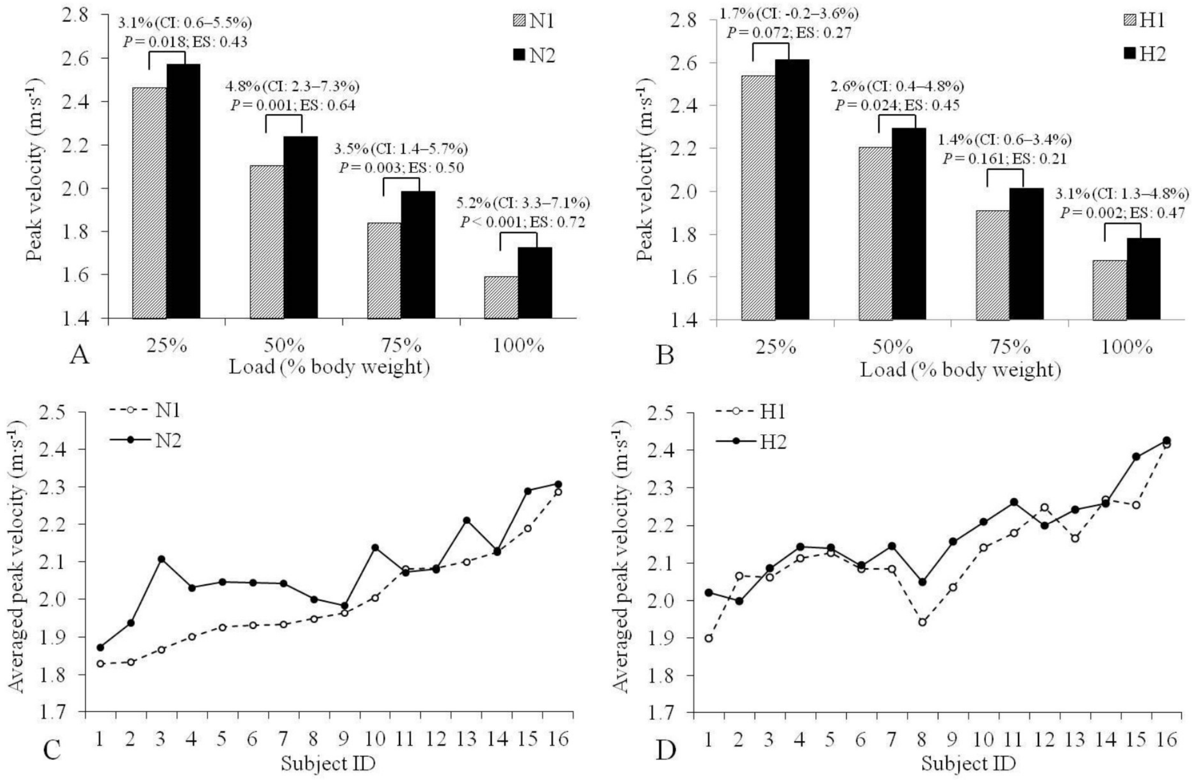

Figure 12. *Chronic effects of the altitude training camp on peak bar velocity during the loaded jump squat. Graphs A and B show the comparison of mean values with the four loads used. Graphs C and D show individual responses using the average peak velocity value of the four loads. N1, pretest conducted in normoxia; N2, postest conducted in normoxia; H1, pretest conducted in hypoxia; H2, postest conducted in hypoxia; CI, 95% confidence interval; P, statistical significance; ES, effect size ([mean postest – mean pretest] / SD pretest).*

Study VIII

The maximal mechanical capabilities of leg extensors muscles to generate velocity and power improve at altitude

The F–V relationships averaged across the subjects proved to be remarkably strong and fairly linear in both atmospheric conditions ($r^2 > 0.99$; $P < 0.001$) (Figure 13). In addition, the individual F–V relationships showed Pearson's product-moment correlation coefficient of 0.972 (range: 0.90–1.00) at sea level and 0.980 (range: 0.82–1.00) at altitude.

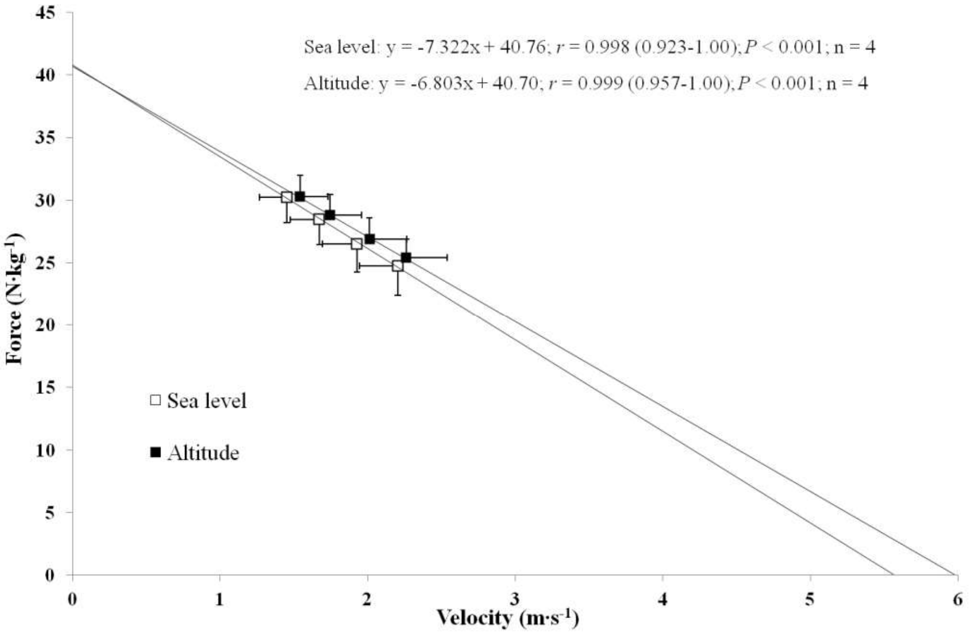

Figure 13. *Simple linear regression models obtained from the data averaged across the subjects force and velocity during squat jump performed under 4 loading conditions. The regression equations are shown with the corresponding Pearson's correlation coefficients and 95% confidence interval.*

The comparison of the parameters calculated from the individual F–V linear regressions between sea level and altitude are presented in Table 20. Significant greater values of V_0 and P_0 were observed at altitude compared to sea level ($P < 0.05$). No significant differences between sea level and altitude were found for F_0 and a parameters ($P > 0.05$).

Table 20. *Comparison of the F–V relationship parameters between sea level and altitude conditions.*

Variable	**Sea level**	**Altitude**	***P***	**Absolute difference (95% CI)**	**%**	**ES**
F_0 (N·kg^{-1})	40.76 ± 2.42	40.77 ± 4.03	0.993	-0.01 (-1.45, 1.44)	0.02	0.002
V_0 (m·s^{-1})	5.71 ± 1.26	6.15 ± 1.19	0.038	-0.43 (-0.03, -0.84)	7.60	0.35
a (N·s·m^{-1}·kg^{-1})	7.47 ± 1.81	6.92 ± 1.74	0.138	0.55 (-0.20, 1.31)	-7.42	-0.31
P_0(W·kg^{-1})	58.31 ± 14.09	62.28 ± 11.71	0.004	-3.96 (-1.42, -6.50)	6.79	0.31

F_0, force intercept; V_0, velocity intercept; a, slope; P_0, maximum power; P, statistical significance; %, Percent difference ([altitude mean – sea level mean] / sea level mean × 100); ES, effect size ([altitude mean – sea level mean] / SDboth); 95% CI, 95% confidence interval.

The comparisons in force, power, and jump height values during the unloaded SJ and CMJ performed in both conditions are shown in Table 21. These 3 variables showed significant, although small, enhancements during the test conducted at altitude for the CMJ. Power output was also significantly higher at altitude in the SJ, but no significant differences were found in force and jump height variables.

Table 21. *Comparison of unloaded squat jump (SJ) and countermovement jump (CMJ) performance between sea level and altitude conditions.*

Jump type	**Variable**	**Sea level**	**Altitude**	***P***	**Absolute difference (95% CI)**	**%**	**ES**
SJ	Peak force (N·kg^{-1})	23.06 ± 2.08	23.33 ± 1.65	0.420	-0.275 (-0.978, 0.429)	1.19	0.15
	Peak power (W·kg^{-1})	50.71 ± 8.50	52.48 ± 7.86	0.028	-1.776 (-3.334, -0.217)	3.50	0.22
	Jump height (cm)	28.1 ± 6.1	29.0 ± 6.1	0.051	-0.879 (-1.763, 0.005)	3.13	0.14
CMJ	Peak force (N·kg^{-1})	24.07 ± 1.38	24.93 ± 1.75	0.010	-0.865 (-1.493, -0.238)	3.60	0.55
	Peak power (W·kg^{-1})	49.60 ± 9.29	51.49 ± 9.13	0.005	-1.892 (-3.138, -0.647)	3.82	0.21
	Jump height (cm)	30.3 ± 7.2	31.4 ± 6.8	0.012	-1.083 (-1.894, -0.272)	3.57	0.15

P, statistical significance; %, Percent difference ([altitude mean – sea level mean] / sea level mean × 100); ES, effect size ([altitude mean – sea level mean] / SDboth). 95% CI, 95% confidence interval.

Study IX

Relationship between vertical jump height and swimming start performance before and after an altitude training camp

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Throughout the camp, daily average pool-sessions were no different between the SLT and AT period, with a total distance swum of 8853 ± 2430 m and 10147 ± 3651 m ($P = 0.538$), total time of 106.9 ± 11.5 min and 113.2 ± 2.0 min ($P = 0.078$), and C-RPE10 scale of 5.74 ± 0.97 and 5.72 ± 0.29 ($P = 0.824$), for SLT and AT respectively.

Dry-land sessions were generally oriented to strength and conditioning. Relative intensity of dry-land session was of 6.16 ± 1.11 vs 5.45 ± 0.62 for SLT and AT, respectively ($P > 0.05$). There was no difference between the total number of resistance training sessions performed in both training periods (code 1: 5.91 ± 2.43 and 5.31 ± 0.65 [$P = 0.479$], and code 3: 4.67 ± 2.08 and 4.31 ± 0.63 [$P = 0.634$] for SLT and AT, respectively. Additionally, an average of two dry-land sessions of code 4 and two of code 5 were completed during the SLT period, while during AT, one session of code 2 and five of code 4 were performed.

The reproducibility of the swimming start skill was confirmed (ICC: 0.90–0.97). At baseline, the time to 15 m was significantly better in the SLT than in the AT conditions ($P = 0.009$; ES = 0.38), whereas no significant differences were obtained for the times to 5 and 10 m. After 3 weeks of training, the SLT produced a significantly slower swimming start time, while no significant changes were observed for the AT (Table 22). The percentage changes revealed significant differences in favour of AT for the times to 10 and 15 meters. The horizontal take-off velocity did not change in any of the training periods.

Table 22. *Pre to post changes in swimming start performance after 3-weeks of sea level (SLT) and altitude training (AT).*

	ICC (90% CI)	Sea level training camp				Altitude training camp			
		Pre	Post	% of change	ES	Pre	Post	% of change	ES
T5 (s)	0.91 (0.79–0.95)	1.63 ± 0.18	1.66 ± 0.15	3.43 ± 4.97	0.21	1.68 ± 0.14	1.69 ± 0.14	0.51 ± 3.14	0.06
T10 (s)	0.97 (0.92–0.98)	4.37 ± 0.42	4.47 ± 0.39*	3.11 ± 2.48	0.24	4.45 ± 0.42	4.41 ± 0.43	-0.89 ± 2.53¥	-0.09
T15 (s)	0.96 (0.90–0.98)	7.26 ± 0.51	7.54 ± 0.61*	4.02 ± 3.26	0.54	7.46 ± 0.54	7.40 ± 0.59	-0.89 ± 2.78¥	-0.12
HTOV (m·s^{-1})	0.90 (0.77–0.95)	4.28 ± 0.25	4.21 ± 0.30	-1.96 ± 3.62	-0.29	4.24 ± 0.31	4.28 ± 0.25	0.33 ± 2.35	0.14

*T5, Time to 5 m; T10, Time to 10 m; T15, Time to 15 m; ICC, Intraclass correlation coefficient; 90% CI, 90% confidence interval; % of change, Percent difference ([Post mean – Pre mean] / Pre mean × 100); ES, effect size ([Post mean – Pre mean] / SDpre); *, Significant differences between pretest and postest (P < 0.05). ¥, Significant differences between percent changes.*

High reliability was observed for the peak velocity achieved with the 4 loads evaluated (ICC: 0.86–0.94). At baseline, LSJ peak velocity was higher for AT compared to the SLT with the 4 loads analyzed ($P < 0.01$; ES = 0.59–0.67). Trivial changes in peak velocity were obtained during the LSJ after each training period (ES: < 0.20), with no significant differences between experimental conditions (Table 23).

Table 23. *Pre to post changes in loaded squat jump peak velocity after 3-weeks of sea level (SLT) and altitude training (AT).*

Load	**ICC (90% CI)**	**Sea level training camp**				**Altitude training camp**			
		Pre ($m \cdot s^{-1}$)	**Post ($m \cdot s^{-1}$)**	**% of change**	**ES**	**Pre ($m \cdot s^{-1}$)**	**Post ($m \cdot s^{-1}$)**	**% of change**	**ES**
25% BW	0.86 (0.69–0.93)	2.15 ± 0.30	2.15 ± 0.28	0.06 ± 5.48	-0.01	2.33 ± 0.28	2.34 ± 0.26	0.67 ± 4.27	0.04
50% BW	0.93 (0.84–0.97)	1.90 ± 0.24	1.90 ± 0.23	-0.24 ± 4.69	-0.03	2.06 ± 0.27	2.06 ± 0.17	0.86 ± 7.28	0.01
75% BW	0.93 (0.84–0.96)	1.63 ± 0.25	1.66 ± 0.21	2.46 ± 6.01	0.12	1.79 ± 0.22	1.80 ± 0.19	1.14 ± 5.74	0.07
100% BW	0.94 (0.86–0.97)	1.44 ± 0.22	1.48 ± 0.19*	2.91 ± 3.38	0.17	1.57 ± 0.20	1.57 ± 0.20	0.78 ± 6.66	0.04

*BW, Body weight; ICC, Intraclass correlation coefficient; 90% CI, 90% confidence interval; % of change, Percent difference ([Post mean – Pre mean] / Pre mean × 100); ES, effect size ([Post mean – Pre mean] / SDpre); *, Significant differences between pre and post ($P < 0.05$). ¥, Significant differences between percent changes.*

DISCUSSION

1) Summary of main findings

The main findings of the present Doctoral Thesis suggest that: (I) the maximum velocity of the bar can be used to predict vertical jump height; (II) the linear velocity transducer is a valid measurement method to assess loaded squat jump performance; (III) the horizontal take-off velocity is the push-off variable most related with swimming start time; (IV) the peak velocity reached during the loaded squat jump proved to be the best indicator of swimming start time; (V) squat jump and bench press performance improve after an acute ascent to altitude; (VI) swimmers that are able to jump higher with additional loads relative to their body weight have a faster swimming start time. In addition, an improvement in vertical jump height following a short-term training program can be used to predict changes in swimming start performance; (VII) the implementation of a power-oriented resistance training during a stay at moderate altitude might enhance the performance of explosive actions such as the loaded squat jump and swimming start time; (VIII) the increase in the maximal mechanical capabilities of leg extensors muscles to generate power after an acute ascent to terrestrial altitude is caused by an increase in the theoretical maximal velocity with no significant changes for maximum force capabilities; and (IX) a typical living high – training high strategy oriented towards the improvement of general strength and endurance capacity has trivial effects on muscular function.

2) Discussion of main findings with previous literature

2.1 Predicting vertical jump height from bar velocity (Study I)

The main finding of *Study I* was that both the maximum velocity of the bar (V_{max}) and the velocity of the bar in the moment just before its acceleration drops below gravity (FPV) were able to predict jump height. Notwithstanding, we feel that V_{max} would be a more suitable indicator for several reasons: a) V_{max} yielded the best-fit prediction (r^2 = 0.931 vs. 0.913); b) the FPV data were heteroscedastic (r^2 = 0.307). This means that FPV tended to be higher than $V_{take\text{-}off}$ recorded by the force plate for loads that can be moved at high velocities, while for heavier loads and thus a lower movement velocity, $V_{take\text{-}off}$ values increased. In contrast, differences between V_{max} and $V_{take\text{-}off}$ showed no clear tendency (r^2 = 0.071), indicating a more random distribution of differences; c) when V_{max} was used as the independent variable, the standard error of the estimate was lower (SEE = 1.47 cm vs. 1.66 cm). This indicates wider limits of agreement range in the Bland-Altman plot; d) for FPV as the independent variable, the regression model showed a tendency to underestimate jump height for extreme velocity values. This compromises the usefulness of this regression model when light and heavy loads are lifted; and finally e) from a practical standpoint, the determination of V_{max} is less time consuming. This is because existing software does not provide the value of FPV and so the data for each repetition need to be exported to individually determine FPV. These results thus suggest that the prediction model adjusted for V_{max} (jump height [cm] = $16.577 \cdot V_{max}$ - 16.384) could be a valid tool for estimating vertical jump height.

Jump ability is a determinant of performance in many sports, including swimming (C. Bishop et al., 2013; West et al., 2011). In effect, ballistic exercises have been described to offer a greater stimulus for improving vertical jump performance compared to traditional resistance training exercises in well-trained athletes (Newton, Kraemer, & Häkkinen, 1999). This determines that training schedules targeted at improving athletic performance often include different types of jump (squat jump, counter movement jump, drop jump, etc.) with or without additional loads (Rebutini, Pereira, Bohrer, Ugrinowitsch, & Rodacki, 2014). Moreover, given its close relationship with sports performance (Breed & Young, 2003; West et al., 2011), jump ability is also often used to monitor the training status of athletes (Prue Cormie, McGuigan, & Newton, 2010; Vuk, Markovic, & Jaric, 2012). In this context, it is advisable that coaches have access to accurate tools to assess lower limb muscular power during such actions (Naruhiro Hori et al., 2007).

Although the force platform is a popular instrument to monitor jump ability (Linthorne, 2001), its use restricted to laboratory conditions, its difficult transport, and especially its price, make it unavailable to most coaches and physical trainers. However, new more portable and cheaper devices are appearing on the market, and these provide valuable information for coaches to plan and monitor the training of their athletes (McMaster et al., 2014). Among these devices, linear transducers of position and velocity are perhaps gaining most popularity in the field of physical training (Harris et al., 2010). These devices enable the coach to record in real time the velocity and power generated by an athlete in each repetition. Based on this type of information, new training protocols can be designed in which the velocity of execution is the criterion for the intensity and volume of the training session (González-Badillo, Marques, & Sánchez-Medina, 2011).

A drawback of these devices is that they do not provide jump height measurements. To address this problem, we have proposed two equations to estimate jump height from the movement velocity of the bar recorded by a linear velocity transducer. V_{max} showed the highest power of prediction ($P < 0.001$; $r^2 = 0.931$; $SE_E = 1.47$ cm). V_{max} was significantly higher than $V_{take\text{-}off}$ for all the loads tested ($P < 0.05$). This was expected since the maximum velocity during a vertical jump is always detected immediately before take-off. Further, the difference between V_{max} and $V_{take\text{-}off}$ appears to be unaffected by the velocity of execution, which is manifested by the negligible association shown in the Bland-Altman plot (r^2 = 0.071). The velocity reached just before acceleration of the bar was lower than gravity (-9.81 $m \cdot s^{-2}$), defined as the final propulsive phase velocity, also emerged as a good predictor of jump height ($P < 0.001$; $r^2 = 0.913$; SEE = 1.66 cm). However, for the reasons indicated above, V_{max} is a more useful tool for this purpose.

2.2 Comparison of the force-, velocity-, and power-time curves recorded with a force plate and a linear velocity transducer (Study II).

The primary finding of Study II demonstrates different shapes of the force-time, velocity-time, and power-time curves between force plate and LVT. The rate of force, velocity, and power development were found to be greater for the LVT during the initial phase of the movement performed with the light load (25%-50%BW), however these differences tended to disappear when the external load was increased (75%-100%BW). On the other hand, at the final phase of the movement larger values were obtained for the force plate at all loads. These results promoted that mean force, mean velocity, and mean power values obtained using a force plate were progressively greater than those using a LVT as the external load was increased. These results contradict the view of some other authors that barbell centre of mass and system centre of mass move in parallel during loaded vertical jumps. Despite this fact, the values of force, velocity, and power obtained using each measurement tool were highly correlated.

Because the kinematic systems (LVT, accelerometers, etc.) are more practical, less expensive and easier to transport than a force plate (Cronin, Hing, & McNair, 2004; Harris, Cronin, Taylor, Boris, & Sheppard, 2010; McMaster et al., 2014), these devices are becoming increasingly popular as a means of determining the athlete´s performance profile (Chiu et al., 2003; Cormie, McBride, et al., 2007; Cormie et al., 2010; Crewther et al., 2011; Cronin et al., 2004; Harris et al., 2010; Sánchez-Medina et al., 2014; Sanchez-Medina, Perez, & Gonzalez-Badillo, 2010) Despite the differences found in the present study in the outcomes measured with force plate and LVT, the very strong correlations obtained between both measurement methods suggest that LVT is useful to monitor the athlete´s performance during vertical squat jumps performed in a Smith machine. Our results showed stronger correlations than those previously reported in the study of Crewther et al. (2011) during the free-weight loaded jump squat at loads of 20, 40, 60, and 80 kg assessed with a linear position transducer. These authors found correlations ranging from 0.59-0.87 and 0.62-0.82 for peak force and peak power, respectively. Presumably, the use of the Smith machine increased the relationship between both measurement tools because it did not allow horizontal movements of the bar. However, our results also agree with previous studies which indicated that the measurement systems (force plate vs. LVT) are not interchangeable (Cormie, Deane, et al., 2007; Cormie, McBride, et al., 2007; Dugan et al., 2004; Hori, Newton, Nosaka, & McGuigan, 2006; Hori et al., 2007; Lake et al., 2012), even if the test is performed in a Smith machine.

In contrast to some previous studies that have shown an overestimation of peak values when the linear position transducer is attached to a free barbell (Cormie, Deane, et al., 2007; Cormie, McBride, et al., 2007; Crewther et al., 2011; Hori et al., 2007; Li et al., 2008), our results in a Smith machine seem to show the opposite. These results may be explained by three key underlying factors: (a) due to the horizontal displacement of the bar during free-weight exercises, the resultant displacement used by the linear position transducers to estimate vertical force, vertical velocity, and vertical power increases, and therefore overestimates these variables; (b) the constant downward force exerted by the cable tension (≈ 5 N in our device) was not taken into account in the calculations (Sánchez-Medina et al., 2014). Because of this, the LVT force was underestimated and the force plate velocity was overestimated. Both factors contributed in such a way that the differences in power output in favour of force plate increased; (c) the friction force with the two linear bearings of the Smith machine vertical bars may have reduced barbell velocity, and therefore also reduced calculated values of force and power recorded by the LVT.

The mean values seemed to be influenced by the different shapes of the force-, velocity-, and power-time curves recorded by both measurement tools. The LVT overestimated force, velocity, and power of system COM during the initial push-off phase (especially with light loads), but underestimated these values during the final push-off phase. These differences between LVT and force plate could be caused by the varying distance between barbell COM and system COM (Hori et al., 2007). This distance changes depending on the external load and could affect the relationship between force plate and LVT (see Figure 14). Therefore, our results showed proportional bias for mean force, mean velocity, and mean power values in favour of force plate as the load was increased.

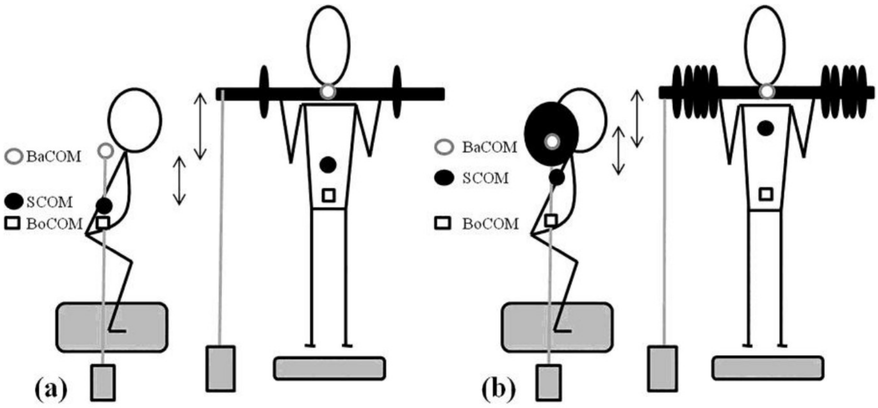


Figure 14. *Theoretical position of body centre of mass (BoCOM), barbell centre of mass (BaCOM) and system centre of mass (SCOM) during squat jumps performed with (a) light load and (b) heavy load.*

However, the problem of detecting the real start and end points of the push-off phase must also be pointed out, because it could affect the results obtained (Hori et al., 2007; Linthorne, 2001). Our decision of setting the arbitrary start point at 5% above system weight for the force plate analysis may have influenced these results, because a greater absolute amount of force (N) was ruled out as the load was increased. On the other hand, it is probable that the LVT needs to reach a certain velocity threshold (voltage) to register that a new repetition has started, and this point may not exactly match with the initial point recorded by the force plate. In addition, although the time point when the acceleration of the barbell became -9.81 m/s^2 has been used to determine the end of the concentric phase (Hori et al., 2007), this point may not exactly match with the real take-off (A García-Ramos et al., 2015). The problem of setting the real start and end points of the push-off could be responsible of the higher CV obtained for mean values of velocity and power compared to their peak values.

Previous studies using these devices have reported both mean values (P Cormie, McBride, et al., 2007; Prue Cormie et al., 2010; McMaster et al., 2014; Sleivert & Taingahue,

2004) and peak values (P Cormie, McBride, et al., 2007; Prue Cormie et al., 2010; Crewther et al., 2011; Li et al., 2008; Newton et al., 1999; Vuk et al., 2012). Despite the fact that mean values were believed to be more reliable (Hori et al., 2006), nowadays there seems to be consensus that peak values should be chosen (Dugan et al., 2004; Hori et al., 2007). In addition, it has been reported that peak values are more related to jump performance (Dugan et al., 2004; Harman, Rosenstein, Frykman, & Rosenstein, 1990; Hori et al., 2006). The main issue of mean values is that they are very influenced by arbitrary decisions about how to determine the exact points of start and end of the concentric phase, making it difficult to obtain accurate measures (Hori et al., 2007; Linthorne, 2001), whereas in contrast peak variables are less affected by these decisions. Based on the results of the present study (proportional bias in mean values and greater CV of mean values especially for velocity and power variables), we also share the view of the studies that recommend using peak values rather than mean values for the assessment of squat jump profiles (Dugan et al., 2004; Hori et al., 2007).

2.3 Relationship between different push–off variables and start performance in experienced swimmers (Study III).

Study III aimed to identify among the large amount of variables that can be collected during the starting push–off phase, the ones that are most related with start performance evaluated with the times to 5, 10 and 15 metres. Surprisingly, our results showed that many of the variables which are frequently reported as a criterion of an optimal swimming start push–off phase were not well correlated to the times to 5, 10 and 15 metres. The average horizontal acceleration, the horizontal take–off velocity, and the resultant take–off velocity were the only variables shown to be significantly correlated to all the times analysed in both freestyle and undulatory starts performed. These variables showed large correlations with the times in both starts analysed (r = -0.52 to -0.69), while the average horizontal acceleration showed a very large correlation (r = -0.71) with the time to 5 metres in the freestyle start.

The horizontal take–off velocity and the average horizontal acceleration were the two best predictors of start performance at the three distances analysed. Since both variables practically explained the same variance, only the one with the highest Pearson's coefficient entered in the multiple regression model. Our results agree with previous studies that have identified the horizontal take–off velocity as the push–off variable that most affects start performance (Tor et al., 2015). Tor et al. (2015) indicated that horizontal take–off velocity can explain 80% of the variance in overall start performance (time to 15 metres). The larger amount of variance explained in the study of Tor et al. (2015) could be caused by the higher heterogeneity of their study sample (male and female were included in the same analysis) compared to our study sample (females from the Slovenian national swimming team). Unfortunately Tor et al. (2015) did not report the descriptive values of the starts performed by their swimmers. On the other hand, the vertical take–off velocity and the average vertical acceleration were able to explain some variance at 5 and 10 metres. The regression models seem to indicate that for a same horizontal take–off velocity, the swimmers with higher vertical take–off velocity (or average vertical acceleration) were faster at these distances. However, these two variables were not included in the regression models which predicted the time to 15 metres.

The average value of the resultant take–off velocity achieved in our study (4.03 ± 0.30 $m \cdot s^{-1}$) was slightly smaller in comparison to that previously reported by Benjanuvatra et al. (2007) in nine elite competitive female swimmers (4.10 ± 0.35 $m \cdot s^{-1}$) (ES = -0.22), but in contrast, the time to 15 metres in our study was better (8.07 ± 0.39 s vs. 8.15 ± 0.34 s; ES = -

0.22). In addition, the resultant take–off velocity reported by Breed and Young (2003) in twenty–three non-competitive female swimmers (3.44 ± 0.3 $m \cdot s^{-1}$) was lower in comparison to our study sample (ES = -1.97). However, despite the fact that resultant take–off velocity is widely used to determine swimmers' efficiency during the push–off phase, the horizontal take–off velocity could be more appropriate. The procedure for calculating the resultant take–off velocity promotes that for a same horizontal take–off velocity, two vertical take–off velocities of the same magnitude but different sign (positive or negative), will produce resultant take–off velocities of the same magnitude. This means that if two swimmers have the same resultant take–off velocity, the swimmer with the higher vertical take–off velocity could have an advantage because he/she will advance longer time out of the water, and therefore with less resistance. The better correlation of horizontal take–off velocity to all distances in both starts performed could support this assumption.

Other parameter which is frequently reported as a criterion to determine swimmers efficiency during the push–off phase is peak horizontal force (Kilduff et al., 2011; West et al., 2011). However, our results indicated that this variable was not significantly correlated to swimming start performance. In addition, when this variable was expressed normalised by swimmer body mass (peak horizontal acceleration) significant correlation was only found to the time to 15 metres in the undulatory start (r = -0.50), but the correlations with freestyle performance remained low (r = -0.14 to -0.27). Therefore it seems that the peak horizontal force, either in absolute or relative values, is not the best parameter to determine swimmers efficiency during the push–off.

Another aspect that draws our attention is that none of the variables related to the application of vertical force (take–off angle, average vertical force, peak vertical force, vertical impulse, vertical take–off velocity, average vertical acceleration, and peak vertical acceleration) was correlated to the swimming start performance. These results could indicate that swimmers should focus their training to improve preferably the horizontal force component. In this regard, Rebutini et al. (2014) showed that plyometric long jump training may improve swimming jump starts, and suggested that this type of training would be more effective than vertical jump training in improving start performance.

Finally, the push–off time showed a large significant correlation to the time to 5 metres in both starts performed, but no significant correlations were found to times measured at longer distances. Although a shorter block time may be preferred, swimmers must be aware that when this phase is too short they cannot produce enough impulse, and therefore the take–off velocity will also be reduced. The horizontal take–off velocity depends on horizontal impulse and body mass (horizontal impulse × body mass^{-1}). The horizontal impulse is calculated as the average horizontal force multiplied by time. Therefore, when the duration of the push–off phase is reduced, the impulse and consequently the take–off velocity will be also decreased. Thus, swimmers should find the optimal balance between block time and take–off velocity (Barlow et al., 2014). It is perhaps because of this fact that no correlation with times to 10 and 15 metres were found.

2.4 The relationship between the lower-body muscular profile and swimming start performance (Study IV).

Study IV aimed to examine the correlation between swimming start performance evaluated by the times required to reach 5, 10 and 15 m and different strength and power tests. The main findings were: i) the peak velocity and peak power normalised per kg of body mass obtained during the SJ with additional resistance showed the highest correlation to swimming start performance; (ii) peak power normalised per kg of body mass and the take-off velocity achieved during the unloaded CMJ showed correlations to the time to 5 and 10 m, but the same variables collected during the unloaded SJ only showed significant correlations to the time to 5 m; (iii) no significant correlations between measured times and isometric leg extension and flexion torques were found. Taken together, the results of the present study showed that loaded jumps were the test that showed the strongest correlation to swimming start performance, i.e. times at 5, 10 and 15 m. The best indicator of overall swimming start performance was the assessment of the peak velocity of the bar during the SJ with additional resistance.

It is interesting to note that the correlations between variables obtained during the two jumps without additional weights (SJ and CMJ) and start performance tended to decrease with increasing distances (correlation to T5 > correlation to T10 > correlation to T15). Both jumps presented significantly large correlations to T5, while T10 only presented a moderate correlation to the CMJ. On the other hand, there were no significant correlations between T15 and both jumps. Our results do not support the findings of West et al. (West et al., 2011) who found correlations of the start time to 15 m with CMJ height. Discrepancy between the obtained results could be due to the differences in the subject sample, e.g. a highly specific group of subjects consisting only of elite male sprint crawl specialists was used in that study, while our sample consisted of the complete female national squad, regardless of their distance and swimming style preferences. On the other hand our results confirm the findings of some previous studies which showed that on land tests were more related to shorter times, i.e. time to swim to 5 m or solely to the above water phase of start (Benjanuvatra et al., 2007).

By failing to show a significant correlation with T15 these results could indicate that the jumps without additional weights are not optimal indicators of overall starting performance (commonly defined as the time to 15 m). As was previously pointed out by De la Fuente et al. (2003), it seems that apart from the starting action on the block, other factors that are mainly related to underwater gliding and swimming contribute to the final starting performance time (T15).

In our study jumps with additional weights were the only test which showed significant correlation to overall swimming performance (T15). In addition, significant correlations to T5 and T10 were also found. Among the large number of variables analyzed in the present study, the peak velocity of the bar reached during the SJ performed with different external loads relative to swimmers' body mass was the one that showed the highest correlation with swimming start performance. The magnitudes of the correlations were similar in the four loads analyzed (large or very large). Our results are consistent with Jidovtseff et al. (2014) who compared eight different vertical jumps and reported that during CMJ loaded with additional 20 kg weight the highest total impulse (corresponded to the area under the force curve) was produced. Based on this fact and despite the decreased eccentric and concentric velocities measured during loaded jumps with respect to other jumps, the authors concluded that loaded jumps were an excellent exercise to solicit high force level in specific durations and as such the longer impulses associated with this jump may be important to improve activities such as the initial acceleration phase in actions such as the take-off.

Although knee and hip extension muscles are of paramount importance for a vertical or any other jump (Spägele et al., 1999) (e. g., the push-off action on the starting block), our results failed to demonstrate significant correlation between isometric strength tests and T5, T10 and T15. The fact that the two-joint muscles activated during the jump, m. rectus femoris and the hamstring group contract at very low velocities and therefore work nearly isometrically (Umberger, 1998), should justify the use of knee extension and flexion isometric strength tests to look for a correlation to different jumping performances. Indeed, it was reported that swimmers who were able to develop greater maximal force and greater rate of force development during isometric leg extension tend to achieve better times in the initial 10 m (Beretić, Durovic, Okičić, & Dopsaj, 2013). However the results of the present study are not consistent with these findings as the knee extension and flexion isometric torque assessed failed to show significant correlations with swimming start performance. The lower specificity of our isometric tests could be responsible for these discrepancies; while force during simultaneous knee and hip extension was measured by Beretić et al. (2013), knee extension and knee flexion were measured separately in our study. Therefore, hip extension isometric test would be a better choice for the evaluation of hamstring muscles than knee flexion test. On the other hand, Baker et al. (1994) have already questioned the validity of isometric tests to monitor dynamically induced training adaptations, as they found that the measures of dynamic and isometric strength were unrelated and therefore assumed that mechanisms that contribute to enhanced dynamic strength appeared unrelated to the mechanisms that contribute to enhanced isometric strength. In addition, Thomas et al. (2015) have recently suggested that dynamic strength tests should be preferred over isometric tests to assess the relationship between relative strength and dynamic performance.

2.5 Effect of acute exposure to moderate altitude on muscle power: hypobaric hypoxia vs normobaric hypoxia (Study V).

The main finding of *Study V* was the enhancement of the force-velocity curve after an acute exposure to a moderate altitude compared to negligible effects of simulated conditions of hypoxia. Contrary to conditions of normoxia or simulated hypoxia, real hypoxia resulted in a faster velocity of the barbell and a higher P_{mean} for a given load in the bench press exercise, which led to a higher load corresponding to P_{max} (+3.29%) and a gain in 1RM (+5.73%) ($P < 0.05$). Thus, real altitude improves the velocity of a loaded movement and it seems that this effect is more linked to the reduced density of air than to diminished availability of O_2.

Although previous research has investigated whether a period of resistance training performed while breathing normobaric hypoxic air can induce muscle hypertrophy (Kon, Ikeda, Homma, & Suzuki, 2012; Nishimura et al., 2010), power and velocity of the movement have not been frequently examined or controlled. Only Scott, Slattery, Sculley, Hodson, & Dascombe (2015) monitored power and force trends over 5 sets of 5 repetitions at 80% of 1RM under acute moderate and high normobaric hypoxia, showing no differences from normoxic conditions. However, the exposition to a real altitude improves performance in short-duration actions such as throws, jumps, or launching objects (Hamlin et al., 2015; Levine et al., 2008).

Despite of limited evidence, there is increasing research examining the physiological effects of hypoxia on resistance training. A recent review of resistance training adaptation mechanisms described a relationship between metabolic stress induced by the build-up of H+ or by low O_2 saturation and the recruitment of additional fast twitch muscle fibers (Schoenfeld, 2013). Then, one possibility is that ascent in altitude induce an anaerobic morpho-functional profile that improves the recruitment of high threshold motor units leading to perform the movement faster. But in an opposite way, the lack of changes in peak and mean power in G2 breathing air impoverished in O_2 (FiO_2 15.7%) questions this idea.

One of the limitations of this study is that the design does not allow us to determine whether or not there are interaction effects between the change in air density and the low O_2 pressure of the air breathed by the subject on the power recorded. On that purpose, a third experimental condition at real altitude breathing a 21% FiO_2 should have been included.

2.6 Relationship between vertical jump height and swimming start performance before and after an altitude training camp (Study VI).

The results of Study VI revealed significant increments in swimming start and loaded SJ performance after a training period at terrestrial altitude. The association between jumping performance and start time previously described by West et al. (2011) was also confirmed in the present study. Additionally, this was the first study that related the changes in jump performance to the changes in swimming start performance after a short-term training program. The large correlations observed between the change scores highlight the relevance of lower-body muscular power in swimming start performance.

Swimming start performance, commonly defined as the time elapsed from the starting signal until the swimmer's head crosses the 15 meter mark (Barlow et al., 2014; West et al., 2011), has been identified as a good predictor of overall race time in the four swimming strokes (Mason & Cossor, 2000). The longest and probably the most important part of the start is the underwater phase (Elipot et al., 2009; Tor, Pease, Ball, & Hopkins, 2014). For this reason, nowadays many coaches are interested in knowing the proficiency of their swimmers during this phase. A possible way to focus analysis on the underwater phase is by demanding that the swimmers only use underwater undulatory kicking, as happens in the butterfly stroke (García-Ramos et al., 2015). The present study provides reference values of undulatory swimming start performance in a group of male Spanish international swimmers. These results were better than those previously reported for women from the Slovenian national team at 5 (1.76 ± 0.13 seconds, ES: 1.79), 10 (4.83 ± 0.29 seconds, ES: 3.15) and 15 meters (8.56 ± 0.57 seconds, ES: 2.68) (García-Ramos et al., 2015).

Unfortunately, there are few studies that investigate the effect of a short-term resistance training program on the development of swimming start performance (i.e., start time). Bishop, Smith, Smith, & Rigby (2009) examined the effect of an 8-week plyometric training program (2 hours per week) on the start time to 5.5 meters in adolescent swimmers. A significant decrease of 0.59 seconds (3.88 ± 0.48 vs. 3.29 ± 0.47) was observed after training. Small improvements were observed in the present study for the times to 5 meters (-0.042 seconds; 1.58 ± 0.09 vs. 1.54 ± 0.09), 10 (-0.109 seconds; 4.08 ± 0.21 vs. 3.97 ± 0.22), and 15 meters (-0.224 seconds; 7.30 ± 0.46 vs. 7.07 ± 0.44). The higher standard of our study sample (faster times) and the differences between training programs (e.g., 8 weeks vs. 2 weeks) could be responsible of these results.

More studies have been conducted to examine the effect of a short-term resistance training program on vertical jump performance. Breed & Young (2003) aimed to determine whether a 9-week resistance training program designed to increase vertical jumping ability could also enhance dive start performance (flight distance) in female students. Countermovement jump height significantly increased by more than 10% after training. But unexpectedly, despite the large to very large correlations observed in the pretest between flight distance and countermovement jump height ($r = 0.60$ to 0.84; $P < 0.01$), flight distance did not improve after training. These results suggest that improvement in jumping ability may not be transferred directly to the skill of diving. Unfortunately, no temporal analysis was performed in this study, because the authors believed that novice swimmers would have too much variation between trials in the underwater phase. In contrast, significant improvements in both skills (squat jump height and swimming start performance) were observed in the present study. This result could be caused by the additional time devoted to practicing the skill of diving in our study (≈ 15 min per day). Therefore, we share the view of other authors that recommend practicing the skill of diving together with resistance training (Benjanuvatra et al., 2007; Breed & Young, 2003).

Jump performance has been deemed to be the skill most related to swimming start performance (Bishop et al., 2013; West et al., 2011; Zatsiorsky, Bulgakova, & Chaplinsky, 1979). West et al. (2011) reported a significantly inverse relationship between the start time to 15 meters and countermovement jump height (r = -0.69) in a group of eleven male international sprint swimmers. Similar correlations were observed in the present study for the squat jump performed with additional loads relative to swimmers' body mass. Additionally, to the best of our knowledge, this is the first study that relates the changes in jump performance with the changes in swimming start performance after a short-term training program. Our results revealed that the swimmers with the largest increments in jump height after training were also those who most improved swimming start performance. These findings further emphasize the importance of possessing a high level of lower-body muscle power to improve starting performance.

2.7 The effect of acute and chronic exposure to hypobaric hypoxia on loaded squat jump performance (Study VII)

Study VII aimed to analyze whether the beneficial effects in explosive actions that follow a sudden ascent to altitude are maintained after a chronic exposure of 15-17 days to a moderate real altitude. The results revealed significant increments in loaded squat jump performance when the tests were performed in hypoxia compared to normoxia in both pretest (6.5%) and postest (4.5%) conditions. Given that the improvements caused by the physical factors should be similar in both tests, the 2.0% difference could be caused by physiological changes which occur during the stay at altitude. In addition, an overall increase in the load-velocity relationship after the altitude training period was also observed. These results suggest that altitude training could constitute a favourable stimulus for the development of explosive actions performance. However, the presence of a control group training in normoxia would have been recommended to examine further whether altitude training really has an additional benefit compared to training at sea level.

Contrary to the deterioration in aerobic performance widely described at altitude, some studies have shown that the performance of non-aerobic dependant explosive actions, improves at altitude (Hahn and Gore, 2001; Kenney et al., 2012; Levine et al., 2008). In accordance with our results, an increase in the velocity at which a determined absolute load can be lifted following a sudden ascent to altitude has also been described (Chirosa et al., 2006; Feriche et al., 2014). The improvements in movement velocity at natural altitude may be caused by different factors such as: (a) a reduced external resistance to the movement due to physical factors (Hahn and Gore, 2001; Kenney et al., 2012; Levine et al., 2008; Peronnet et al., 1991); (b) an incremented ability of the subject to produce force due to a stimulation of physiological factors, such as an additional recruitment of fast twitch muscle fibers (Schoenfeld, 2013) or (c) a combination of physical and physiological factors.

The reduction in the external resistance to the movement has been proposed as one of the main reason for the improvements in explosive actions performed at altitude (Hahn and Gore, 2001; Kenney et al., 2012; Levine et al., 2008). Peronnet et al. (1991) indicated that running speed in sprint events (100 and 200 m) is faster as altitude increases (up to 4000 m), due to the progressive reduction in air resistance without the detrimental effect of reducing energy availability. In addition, Feriche et al. (2014) compared the effects of acute exposure to real (hypobaric hypoxia) or simulated altitude (normobaric hypoxia, 15.7% inspired fraction of oxygen) on the force-velocity relationship during a bench press exercise in two groups of athletes from combat sports. While the group tested in hypobaric hypoxia showed an increase of 5.7% in bench press one-repetition maximum, as well as a faster velocity for a given load compared to normobaric normoxia, no changes in any of these variables were observed in the group tested in normobaric hypoxia.

However, the slow velocities produced during loaded squat jumps suggest that it is unlikely that all differences can be explained by the physical factor alone (lower air resistance). In addition, if physical factors were the only cause, the same differences between hypoxia and normoxia would be expected in both tests. Nonetheless an increase of 6.5% in the overall load-velocity relationship considering the data from the pretest and 4.5% considering the data from the postest were observed in hypobaric hypoxia. Given that air resistance was similar in both tests, the 2.0% difference could be explained by changes in physiological factors during the stay at altitude.

Chronic hypoxia has been frequently associated with the loss of muscle mass (Deldicque and Francaux, 2013; Mizuno et al., 2008) and its functional capacity (Felici et al., 2001; Ferretti et al., 1990; Narici and Kayser, 1995; Raguso et al., 2004). However, most of these studies were conducted at high altitude (> 5000 m asl), while altitude camps are usually held at moderate altitudes (1800-2500 m asl). Despite the fact that an ascent to moderate altitude seems to improve the performance of explosive actions (Feriche et al., 2014), there is a lack of longitudinal studies analyzing the effects of altitude training camps on explosive muscle performance. In this context, the results of the present study revealed an overall increment of 4.0% in loaded squat jump velocity after the altitude training period when normoxia tests, before and after the camp, were compared.

A wide variability in aerobic adaptations between individuals after altitude training is frequently reported (Friedmann et al., 2005). However in the present study only one swimmer in the pretest and another swimmer in the postest developed higher velocity values during the tests conducted in normoxia. In addition, when considering the data from normoxia tests, 75% of the swimmers (n = 12) improved loaded squat jump performance by more than 1%, whereas the changes in the remaining swimmers (n = 4) was ± 1%. Therefore, the altitude training camp worked well for most of the swimmers.

2.8 The maximal mechanical capabilities of leg extensors muscles to generate velocity and power improve at altitude (Study VIII)

Study VIII aimed to analyze the effect of an acute ascent to a moderate altitude on the maximal mechanical capabilities of leg muscles to generate force, velocity, and power. The primary finding of this study revealed higher magnitudes of V_0 and P_0 parameters at altitude, while F_0 remained unaffected by the change in the environmental condition. In addition, the peak values of force, power, and jump height recorded during the unloaded jumps were also generally higher at altitude, being more pronounced in the CMJ. These results confirm the potential effect of an acute exposure to real altitude on enhancing vertical jump performance. The increase in maximum power of the leg extensors at altitude was caused by an increase in the theoretical maximal velocity at which lower limbs can extend with no significant changes for the theoretical maximal force.

Performance in multi-joint tasks seems to be strongly determined by P_0 and the F–V profile of the neuromuscular system involved in the movement (Jiménez-Reyes et al., 2014; Samozino et al., 2014; Samozino, Rejc, Di Prampero, Belli, & Morin, 2012). In this context, the F–V relationship parameters (F_0, a,V_0, and P_0) are being used to evaluate the maximal mechanical capabilities of the human musculoskeletal system as well as to monitor athletes' training status (Jiménez-Reyes et al., 2014; Nikolaidis, 2012; Samozino et al., 2012). The present study revealed that an acute ascent to altitude has a significant effect on the F–V relationship obtained during loaded vertical jumps. Specifically, a statistically significant increase of 6.8% in P_0 was obtained at altitude compared to sea level conditions. This increase was caused by a significant enhancement of 7.6% in V_0. However, F_0 was unaffected after an acute exposure to altitude (differences of 0.02%). These results suggest that exercising at altitude may be beneficial for the performance of high speed actions (e.g., tennis serve, handball throw, volleyball shot, etc.). Despite the fact that resistance training under hypoxic conditions has been shown to be more effective than normoxic training in improving explosive force (Manimmanakorn et al., 2013), additional longitudinal studies are needed to confirm these findings.

Previous studies have already confirmed the linearity of the F–V relationship using both force platforms (Cuk et al., 2014; Jiménez-Reyes et al., 2014) and linear transducers (Meylan et al., 2015; Sreckovic et al., 2015) as the measuring tools. Cuk et al. (2014) tested the linearity, reliability, and validity of the F–V relationship parameters obtained with a force platform during different vertical jumps (SJ, CMJ, and CMJ with arm swing). These authors concluded that the F–V relationship obtained could be exceptionally strong, fairly linear, highly reliable, and of a moderate-to-high validity. Specifically, they reported median correlation coefficients for the F–V relationship ranging between 0.919 and 0.989. The two median correlation coefficients obtained in the present study (sea level and altitude conditions) were higher than 0.99, supporting the combined use of force platforms (which directly measures force) and linear velocity transducers (directly measuring velocity) to determine the F–V relationship during vertical jumps. The stronger linearity of the F–V relationship in the present study could be caused by the direct measurement of force and velocity variables (no estimation was needed), since it is known that the manipulation of the raw data can magnify the measurement error (Cormie, Deane, et al., 2007; McMaster et al., 2014).

Unloaded SJ and CMJ performances between sea level and altitude conditions were also compared in order to further examine the effect of an acute exposure to altitude on the capability of leg muscles to generate force, velocity, and power. These two jumps are probably the most commonly used in basic research, as well as in sport training and testing, since they have shown to maximize power output (Vuk et al., 2012). To the best of our knowledge, this is the first study that uses a force platform to compare force, velocity, and power variables in the SJ and CMJ exercises between sea level and moderate altitude conditions. The results revealed an increase in the values of force (1.2–3.6%), velocity (1.6–1.9%), and power (3.5–3.8%) after ascent to altitude. The use of a force platform instead of a linear transducer can rule out the physical factor (i.e., lower aerodynamic resistance at altitude) as the only responsible factor for the greater velocities reached at altitude for a same absolute load (Feriche et al., 2014; García-Ramos et al., 2014). The results of the present study suggest that subjects are able to apply more force at altitude, and therefore that air resistance is not the only cause of the higher velocity observed at terrestrial altitude.

2.9 Relationship between vertical jump height and swimming start performance before and after an altitude training camp (Study IX).

Study IX investigated the effectiveness of an altitude training camp on swimming start and loaded SJ performance. Both training periods caused similar small changes in the analyzed variables. However, it should be noted that the training regime followed by the swimmers, which was strongly oriented towards improving endurance capacity, did not allow us to identify whether or not power-oriented AT might genuinely enhance the contractile force of the muscles and consequently the performance of explosive actions. Nevertheless, the results of the present study suggest that a training high living high strategy of 3 weeks at 2320 m asl does not have adverse effects on muscular function, even if swimmers do not focus their training solely on improving force and power.

This is one of the first studies evaluating the performance of explosive actions (swimming start time and LSJ) after an altitude training camp held at terrestrial moderate altitude (2320 m asl). Both training periods promoted similar changes in the analyzed variables. These results have important applications in the field of altitude training as they indicate that 3-weeks of a training high – living high strategy does not constitute a negative stimulus on muscular function. Therefore, it would seem unnecessary for swimmers to be concerned about the loss of lean mass and its functional capacity when living and training at moderate altitude.

The changes in swimming start time observed after the AT camp represented a little but significant improvement over the SLT period. However, rather than attributing this to the effect of the AT training camp, we should acknowledge that this result was mainly caused by the significant impairment in swimming start time observed after the SLT period. The training regime followed by the swimmers was excessively oriented towards the improvement of endurance capacity which could explain this result since it is known that concurrent endurance training attenuates strength training responses (Rønnestad et al., 2012).

In this regard, Häkkinen et al. (2003) reported that concurrent strength and endurance training leads to interference in explosive strength development. Therefore, since explosive strength is paramount for the actions analyzed in the present study (LSJ and swimming start) (West et al., 2011), it is logical that the improvements recorded in LSJ performance were not very pronounced. Similar weak enhancements in LSJ were produced after each training period (SLT and AT). These results confirm that a typical 3-week concurrent strength and endurance training program performed at terrestrial altitude does not have adverse effects on vertical jump performance in high level swimmers.

While the majority of studies carried out with swimmers at altitude have been focused on parameters related to aerobic metabolism (Rodriguez et al., 2015), this is the first study examining the effect of a traditional AT camp on the performance of explosive actions. The main conclusion of the present study is to report that the performance of explosive actions is not impaired after a stay of 3 weeks at terrestrial altitude even if swimmers do not change their strength training routine in an attempt to improve these functions. However, it would be necessary for future studies to carry out resistance training programs exclusively designed to develop maximum and explosive strength to further explore the applications of AT in the field of strength and conditioning. Due to logistical constraints it was not feasible to split the national team in 2 groups to counterbalance the order of the training interventions. To minimize the impact of this potential limitation only the swimmers older than 16 years at the beginning of the first phase of the study were included in the analysis.

LIMITATIONS AND STRENGTHS

Limitations

The studies comprising the present Doctoral Thesis present several potential limitations that must be acknowledged. Firstly, the main sample of this Doctoral Thesis was composed by the whole Slovenian national team. Although this could also be seen as a strength, the inclusion of swimmers which compete in different distances (i.e., sprint and endurance) and swimming styles (i.e., crawl, breaststroke, backstroke, and butterfly) could have affected some results. For example, while significant correlations between start time to 15 m and unloaded CMJ height have been reported in a highly specific group of elite male sprint crawl specialists (West et al., 2011), we have failed to show significant correlations between both variables. Secondly, a control group training in normoxia would have been necessary in Studies 6-7 to examine further if strength training at altitude really has an additional benefit compared to training at sea level. Thirdly, due to logistical constraints it was not feasible to split the Slovenian national team in two groups to counterbalance the order of the training interventions (Study IX). To minimize the impact of this potential limitation only the swimmers older than 16 years at the beginning of the first phase of the study were included in the statistical analysis. Finally, although swimmers are one of the athletes that most commonly use altitude training, their training routine excessively oriented towards the improvement of endurance capacity was not the optimal to elucidate the potential applications of altitude training on improving muscular power. This is because has been shown that concurrent endurance training attenuates strength training responses (Häkkinen et al., 2003; Rønnestad et al., 2012). Nevertheless, the results of the present Doctoral Thesis suggest that a training high living high strategy of 3 weeks at 2320 m asl does not have adverse effects on muscular function, even if the training goals are mainly focused on endurance performance.

Strengths

One of the strengths of the present Doctoral Thesis is the high quality of the sample tested, all members from the Slovenian or Spanish national teams. Therefore, for the first time, we have been able to document the effect of a traditional training camp of high level swimmers held at moderate altitude on the performance of explosive actions such as vertical jumps and the swimming start. In addition, it should be acknowledged the high quality of the materials (force platforms, linear transducers, high speed cameras, etc.) and procedures followed that have allowed us to determine the dependent variables of the present Doctoral Thesis accurately. Finally, the funding received to conduct this project (DEP2012-35774) has allowed us to constitute a multidisciplinary team with specialised researchers from the University of Granada, University of Ljubljana, and the High Performance Center of Sierra Nevada.

FUTURE DIRECTIONS IN RESEARCH

The three topics covered in the present Doctoral Thesis are currently objectives of further investigation in our research group:

A) Refining the methodology of strength testing. Studies focused on the reliability and magnitude of mechanical variables (force, velocity, and power) during different types of vertical jump will provide valuable information for both refining and standardizing the testing methodology, as well as for creating standards for measuring mechanical capacities of leg muscles.

B) *Association between different strength manifestations and swimming start performance*. Currently we are developing a similar analysis to study the association of the different strength manifestations evaluated with the performance in the "swimming turns" that were also performed by the swimmers tested in the present Doctoral Thesis.

C) Effect of altitude training on the performance of explosive actions. To overcome the limitations commented above, our research group has recently received funding to study the influence of moderate altitude exposure on muscular power adaptations (DEP-2015-64350-P; MINECO/FEDER). Specifically, we are exploring different hypoxic training strategies of power-oriented resistance training at moderate altitude. The results of this project are expected to give further insight regarding the applications of altitude training in the field of strength and conditioning.

CONCLUSIONS

General

Our results have shown a clear effect of altitude exposure on muscle function. The velocity at which a determined absolute load can be lifted in exercises such as the bench press and the loaded jump squat is higher when performed at altitude compared to normoxia conditions. No significant differences between normobaric hypoxia and normoxia conditions could suggest a major effect of air resistance. However, the maximum power estimated from the force platform data during the unloaded SJ and CMJ was also higher after an acute ascent to altitude, which suggest that the lower aerodynamic resistance at altitude is not the only cause of the greater velocities reached at altitude. Regarding the adaptations after altitude training, it was demonstrated that the implementation of power-oriented resistance training during a stay at moderate altitude might enhance both loaded squat jump and swimming start performance. However, a typical training high – living high strategy of 3 weeks at 2320 m asl oriented towards the improvement of endurance capacity had trivial effects on muscular function. Finally, we have also confirmed that lower-limb muscle function is highly related to swimming start performance. These findings encourage swimmers to perform lower-body strength and power training in order to optimise swimming start performance.

Specifics

The specific conclusions of the present Doctoral Thesis were:

I. The maximum velocity reached by the bar, which is directly recorded by the linear velocity transducer, can be used to predict jump height.

II. The very high correlations between the outcomes (force, velocity, and power) collected by the linear velocity transducer and the "gold-standard" force platform have confirmed the suitability of the linear velocity transducer to monitor loaded squat jump performance. However, the results show that their outcomes are not interchangeable even if vertical jumps are performed in a Smith machine.

III. The high amount of variance of swimming start time that can be explained solely by the push-off variables highlights the importance of this swimming skill. Horizontal take-off velocity and average horizontal acceleration collected during the push-off phase have proved to be the two variables most related with swimming start performance.

IV. IV. Lower-limb muscle function is highly related to swimming start performance. Among the different dry land test and variables analysed in this study, the peak velocity achieved during a loaded squat jump is the most related to swimming start performance.

V. The maximum dynamic strength (1RM) and the velocity at which a determined absolute load can be lifted in the bench press exercise are higher when performed at moderate altitude compared to normoxia conditions. The no significant differences between normobaric hypoxia and normoxia conditions could suggest a major effect of air resistance.

VI. The implementation of power-oriented resistance training during a stay at moderate altitude might enhance both loaded squat jump and swimming start performance.

VII. Significant increments in loaded squat jump performance in hypobaric hypoxia were observed after an acute (1-3 days) and chronic (15-17 days) exposure to a moderate natural altitude compared to normoxia conditions.

VIII. The increase in the maximal mechanical capabilities of leg extensors muscles to generate power after an acute ascent to terrestrial altitude is caused by an increase in the theoretical maximal velocity with no significant changes for maximum force capabilities. In addition, the maximum power estimated from the force platform data during the unloaded SJ and CMJ is also higher after an acute ascent to altitude.

IX. A typical training high – living high strategy of 3 weeks at 2320 m asl oriented towards the improvement of endurance capacity and general strength has trivial effects on muscular function.

CONCLUSIONES

General

Nuestros resultados han mostrado un claro efecto de la exposición a la altura sobre la función muscular. La velocidad a la que una determinada carga absoluta puede desplazarse en ejercicios como el press de banca y el squat jump sobrecargado es mayor en altura comparado con condiciones de normoxia. La no existencia de diferencias significativas entre la hipoxia normobárica y la condición de normoxia podría sugerir un efecto importante de la resistencia del aire. Sin embargo, la potencia máxima estimada por la plataforma de fuerza durante los ejercicios de salto con y sin contramovimiento también fue mayor tras un ascenso agudo a la altura, lo que sugiere que la menor resistencia del aire en altura no es la única responsable de las mayores velocidades. Respecto a las adaptaciones tras el entrenamiento en altura, se ha demostrado que la implementación que un entrenamiento de fuerza orientado hacia el desarrollo de la potencia muscular puede mejorar el rendimiento del salto vertical sobrecargado y el tiempo en la salida de natación. Sin embargo, una estrategia típica de entrena alto – vive alto de 3 semanas a 2320 m sobre el nivel de mar orientado hacia la mejora de la resistencia tiene efectos triviales sobre la función muscular. Finalmente, también hemos confirmado que la potencia de los miembros inferiores está altamente relacionado con el rendimiento en la salida de natación. Estos hallazgos reflejan la importancia de que los nadadores lleven a cabo entrenamiento de fuerza y potencia de los miembros inferiores para optimizar el rendimiento en la salida de natación.

Específicas

Las conclusiones específicas de la presente Tesis Doctoral fueron:

I. La máxima velocidad de la barra, que es directamente registrada por un transductor lineal de velocidad, puede usarse para predecir la altura de salto.

II. Las altas correlaciones entre los valores de fuerza, velocidad, y potencia registrados por un transductor lineal de velocidad y la plataforma de fuerza (considerada como el criterio estándar) confirman la validez del transductor lineal de velocidad para testar el rendimiento en el ejercicio de squat jump sobrecargado. Sin embargo, los resultados muestras que la magnitud de las variables no son intercambiables entre ambos dispositivos incluso si los saltos se realizan en una máquina Smith.

III. La gran cantidad de varianza del tiempo de salida que puede ser explicado únicamente por las variables derivadas de la fase de impulso pone de manifiesto la importancia de esta fase. La velocidad de despegue horizontal y la aceleración media horizontal probaron ser las dos variables más relacionadas con el rendimiento en la salida de natación.

IV. La función muscular de los miembros inferiores está altamente relacionada con el rendimiento en la salida de natación. Entre los diferentes test de campo y variables analizadas, la velocidad máxima alcanzada durante el squat jump sobrecargado es la más relacionada con el rendimiento en la salida de natación.

V. La fuerza dinámica máxima (1RM) y la velocidad a la que una determinada carga absoluta puede ser desplazada en el ejercicio de press de banca son mayor en altitud moderada comparado con condiciones de normoxia. Las diferencias no significativas entre la hipoxia normobárica y normoxia podría sugerir un efecto relevante de la resistencia del aire.

VI. La implementación de un entrenamiento de fuerza orientado hacia el desarrollo de la potencia durante una estancia en altitud moderada puede mejorar el rendimiento tanto del squat jump cargado como de la salida de natación.

VII. Incrementos significativos en el rendimiento en el squat jump sobrecargado en hipoxia hipobárica se observaron tras una exposición aguda (1-3 días) y crónica (15-17 días) a la altura moderada comparado con la condición de normoxia.

VIII. El incremento de las propiedades mecánicas máximas de los músculo para producir potencia observado tras un ascenso agudo a la altura es causado por un incremento en la máxima velocidad teórica, no existiendo cambios significativos para la máxima producción de fuerza teórica. Además, la potencia máxima derivada de la plataforma de fuerza durante los saltos con y sin contramovimiento sin carga adicional también es mayor tras un ascenso agudo a la altura.

IX. Una estrategia típica de entrena alto – vive alto de 3 semanas a 2320 m sobre el nivel del mar orientada hacia la mejora de la fuerza general y la resistencia tiene efectos triviales sobre la función muscular.

SUMMARY IN SLOVENE

Uvod

Višinski trening predstavlja pomemben del telesne priprave športnikov povsod po svetu in se izvaja z namenom oziroma pričakovanji, da bo izboljšal sposobnosti na normalni nadmorski višini (Bonetti & Hopkins, 2009). Iz tega razloga v svetu obstaja vsaj 22 višinskih centrov, ki so locirani na višini med 1000 in 3000 metrov nadmorske višine. Plavanje je ena izmed športnih panog, kjer se trenerji najpogosteje in redno poslužujejo višinskega treninga (Rodriguez et al., 2015). Center za višinske priprave v Sierri Nevadi (CAR-High Performance Centre of Sierra Nevada) je zaradi optimalne nadmorske višine 2320 m (Bonetti & Hopkins, 2009); Wilber, Stray-Gundersen, & Levine, 2007) in seveda dejstva, da premore 50-metrski bazen, priljubljena destinacija za plavalne priprave.

V največji meri se višinski trening preučuje v povezavi z vplivom na vzdržljivostne parametre (npr. največjo porabo kisika, maso hemoglobina ipd.) in njegova učinkovitost na vzdržljivostne sposobnosti je generalno potrjena oziroma priznana (Govus, Garvican-Lewis, Abbiss, Peeling, & Gore, 2015; Rodriguez et al., 2015).

Po drugi strani učinkovitost višinskega treninga na eksplozivnost oziroma hitro moč ni bila veliko preiskovana. V tem kontekstu smo v tej nalogi preučevali akutni in kronični vpliv izpostavljenosti na zmerni višini na izvedbo eksplozivnih gibalnih nalog kot so navpični skoki in plavalni startni skok. Poleg tega smo želeli ugotoviti povezave med različnimi manifestacijami moči in učinkovitostjo plavalnega starta, ter izpopolniti metodologijo testiranja hitre moči z uporabo tenziometrijske plošče in linearnega merilnika hitrosti.

V smislu veljavnosti in zanesljivosti, za najustreznejšo merilno napravo za merjenje navpičnih skokov velja tenziometrijska plošča (TP) (Cronin et al., 2004; Giroux et al., 2015). Z neposrednim merjenjem sile reakcije podlage in ustreznim računskim pristopom lahko natančno določimo hitrost, moč in pozicijo težišča sistema opazovanja. Ker je tenziometrijska plošča relativno draga naprava se v zadnjem času v športni znanosti uporabljajo cenejše in lažje prenosljive naprave kot je na primer linearni merilnik pozicije in linearni merilnik hitrosti (LMH) (McMaster, Gill, Cronin, & McGuigan, 2014). Slednji je boljši saj direktno meri hitrost premikajočega se objekta, kar zmanjšuje računanje in s tem napako merjenja hitrosti v primerjavi z merilnikom pozicije, kjer hitrost izmerimo posredno kot odvod poti v času (McMaster et al., 2014). Slabost takšnega merilnika, ki je bil uporabljen v tej raziskavi (T-Force System), je da ne moremo neposredno izračunati višine skoka, saj ne moremo izmeriti trajanja faze leta pri skoku oziroma hitrosti v trenutku odriva. Iz tega razloga je bila ena od nalog raziskave tudi ta, da smo preizkusili ali je to vendarle mogoče.

Dober oziroma hiter start je eden od ključnih dejavnikov uspešnosti pri plavalcih najvišjega ranga (Arellano, Brown, Cappaert, & Nelson, 1994; Mason & Cossor, 2000). Učinkovitost starta se meri s časom od startnega signala do 15-ih metrov (Barlow, Halaki, Stuelcken, Greene, & Sinclair, 2014; Seifert et al., 2010), in je odvisen od naslednjih dejavnikov: reakcijskega časa, razvite vodoravne in navpične komponente sile na startnem bloku, učinkovitega drsenja pod vodo in učinkovite propulzije nog pri izplavanju na gladino (Elipot et al., 2009; West, Owen, Cunningham, Cook, & Kilduff, 2011). Največja mišična sila in moč (produkt sile in hitrosti mišice) predstavljata ključna dejavnika pri razvijanju sile ob odrivu na startnem bloku ter pri učinkovitem udarjanju z nogami pod vodo; posledično izboljšanje mišične moči pomeni izboljšanje startnega časa ((West et al.,2011). Trenerji se teh dejstev zavedajo, zato plavalci, predvsem sprinterji, posvečajo pomemben del časa vadbi moči na kopnem (Bishop et al., 2013).

Za ugotavljanje učinkovitega plavalnega starta so bile preučevane številne spremenljivke: največja vodoravna sila med odrivom na startnem bloku (Kilduff et al., 2011; West et al., 2011), največja navpična sila (Kilduff et al., 2011; West et al., 2011), rezultanta hitrosti odriva (Benjanuvatra, Edmunds, & Blanksby, 2007; Breed & Young, 2003), vodoravna hitrost odriva (Slawson, Conway, Cossor, Chakravorti, & West, 2013), kot odriva (Barlow et al., 2014; Benjanuvatra et al., 2007; Breed & Young, 2003; Seifert et al., 2010), čas odriva (Barlow et al., 2014; Benjanuvatra et al., 2007; Breed & Young, 2003; Seifert et al., 2010; Slawson et al., 2013), gibalni čas odriva (Barlow et al., 2014; Benjanuvatra et al., 2007), navpični sunek sile (Benjanuvatra et al., 2007; Breed & Young, 2003), vodoravni sunek sile (Benjanuvatra et al., 2007; Breed & Young, 2003), povprečni vodoravni pospešek med odrivom (Slawson et al., 2013), in največji vodoravni pospešek med odrivom (Slawson et al., 2013). Zaradi očitnega nestrinjanja med raziskovalci, katere spremenljivke so bolj in katere manj pomembne oziroma povezane z uspešnostjo startnega skoka, smo želeli ugotoviti povezanost različnih merjenih spremenljivk s startnim časom merjenim na 5, 10 in 15 metrov, v nadaljevanju pa ugotoviti še, kako so te povezane z nekaterimi spremenljivkami mišične moči.

Primarni cilj raziskave je bil vendarle ugotoviti akutni učinek izpostavljenosti višini in učinek vadbe na višini na eksplozivna gibanja kot so navpični skoki in predvsem startni skok. Dosedanje raziskave so pokazale, da je bil trening na višini povezan z zmanjšanjem puste mišične mase (Deldicque & Francaux, 2013; Mizuno, Savard, Areskog, Lundby, & Saltin, 2008) kakor tudi z njeno funkcionalno kapaciteto (Felici et al., 2001; Ferretti, Hauser, & di

Prampero, 1990; Narici & Kayser, 1995; Raguso, Guinot, Janssens, Kayser, & Pichard, 2004). Razlogi za poslabšanje mišične funkcije naj bi bili učinek hipoksije na presnovo beljakovin (Deldicque & Francaux, 2013; Etheridge et al., 2011), nezadosten vnos energije (Aeberli et al., 2013; Fulco et al., 2002) ali zmanjšan trenažni dražljaj (Feriche et al., 2014; Hoppeler & Desplanches, 1992). Vendar je bila večina teh raziskav, ki so ugotovile poslabšano delovanje živčno mišičnega sistema opravljena na veliki višini (nad 5000 m) in ne na priporočeni višini 2000 – 2500 m (Bonetti & Hopkins, 2009; Wilber et al., 2007).

Po drugi strani so se pri dvigu na višino pokazali akutni učinki na izboljšanje izvajanja eksplozivnih akcij (Hamlin, Hopkins, & Hollings, 2015; Kenney, Wilmore, & Costill, 2012). Chirosa et al. (2006) je pri dvigu iz normalne višine na zmerno (2320 m) v času izpostavljenosti višini od ene do petih ur, poročal o povečani hitrosti izvajanja pol počepa z enako obremenitvijo. Kot eno od možnih razlag so raziskovalci predlagali zmanjšan zračni upor na višini (Hahn & Gore, 2001; Kenney et al., 2012; Levine, Stray-Gundersen, & Mehta, 2008; Peronnet, Thibault, & Cousineau, 1991). Vendar pa se kot možni vzroki navajajo tudi različni fiziološki dejavniki, kot so povečana rekrutacija hitrih mišičnih vlaken (Schoenfeld, 2013) ali pa povečana aktivnost simpatičnega živčnega sistema (Hainsworth et al, 2007).

Za ugotavljanje mehanskih sposobnosti mišic pri proizvajanje sile, hitrosti in moči, predvsem med izvajanjem več-sklepnih akcij (potisk s prsi, skoki), se v lahko uporablja tudi analiza odnosa sila – hitrost (Cuk et al., 2014; Garcia-Ramos, Jaric, Padial, & Feriche, 2016; Jaric, 2015; Samozino et al., 2014). Večina raziskav na višini je merila hitrost premikanja bremena z uporabo linearnega merilnika hitrosti, zato ni bilo moč z gotovostjo trditi ali se je breme gibalo hitreje zaradi zmanjšanega zračnega upora ali pa so mišice iztegovalke nog dejansko hitreje razvijale silo. Da bi rešili to dilemo, je bila v tej raziskavi poleg merilnika hitrosti uporabljena še tenziometrisjka plošča, ki je direktno merila silo reakcije podlage in s tem silo, ki so jo razvile mišice.

Namen, cilji in hipoteze

Namen doktorske naloge je bil preučiti učinek kratkotrajne in dolgotrajne izpostavljenosti zmerni nadmorski višini na živčno-mišično učinkovitost nog, preučiti tipičen trening moči na kopnem vrhunskih plavalcev med podaljšanim bivanjem na zmerni nadmorski višini ter preučiti povezavo med različnimi parametri moči in učinkovitostjo plavalnega starta.

Specifične naloge in hipoteze so bile izpeljane v devetih študijah, ki so imele specialni cilj:

Cilj: izračunati višino navpičnega skoka z uporabo linearnega merilnika hitrosti.

H_1: Z uporabo linearnega merilnika hitrosti je možno dovolj natančno oceniti višino skoka.

Cilj: primerjati in ugotoviti zanesljivost ostalih parametrov navpičnega skoka (sile, hitrosti, moči) izmerjenih s tenziometrijsko ploščo in linearnim merilnikom hitrosti med izvajanjem skoka z dodatnim bremenom v vodilih.

H_2: povezanost parametrov izmerjenih z obema napravama pri skokih v vodilih bo večja kot do sedaj predstavljena povezanost s prostimi skoki.

Cilj: ugotoviti povezanost med različnimi spremenljivkami izmerjenimi s TP med odrivom na startnem bloku in časi plavanja na 5, 10 in 15 metrov.

H_3: spremenljivke izmerjene s TP med odrivom na startnem bloku in časi plavanja na 5, 10 in 15 metrov so povezani. Največjo povezanost s startnimi časi bo imela vodoravna odrivna hitrost.

Cilj: ugotoviti, s kateri testi na kopnem so najbolje povezani z učinkovitostjo plavalnega starta

H_4: dinamični testi (skok iz počepa, skok z nasprotnim gibanjem in skoki z dodatnimi bremeni) bodo bolje povezani s startnimi časi kot testi izometrične moči iztegovalk in upogibalk nog.

Cilj: primerjati učinek kratkotrajne izpostavljenosti hipoksiji na višini (hipobarična hipoksija) in simulaciji višine (normobarična hipoksija).

H_5: Odnos sila-hitrost pri potisku s prsi izmerjen v pogojih hipobarične in normobarične hipoksije se razlikuje.

Cilj: ugotoviti napredek pri višini navpičnih skokov in startnem skoku po tritedenskem treningu na zmerni višini ter ugotoviti povezave med njima.

H_6: višina navpičnih skokov in učinkovitost startnega skoka po tritedenskem treningu na višini se bosta izboljšala, napredka v enem in drugem testu bosta sorazmerna.

Cilj: primerjati rezultate skokov z dodatnimi bremeni po kratkotrajni (1-3) in dolgotrajni (15-17 dni) vadbi na višini.

H_7: napredek v navpičnih skokih z dodatnimi bremeni po vadbi na nižini in po kratkotrajni in dolgotrajni vadbi na višini, se ne bo razlikoval.

Cilj: ugotoviti vpliv kratkotrajne izpostavljenosti zmerni višini na odnos sila-hitrost ter največjo moč pri navpičnih skokih z dodatnimi bremeni ter primerjati rezultate navpičnih skokov na majhni in zmerni nadmorski višini.

H_8: mehanski parametri navpičnih skokov izmerjeni s TP bodo boljši na zmerni kot na majhni višini.

Cilj: oceniti vpliv hkratne vadbe moči in plavalne vadbe na zmerni višini na učinkovitost plavalnega starta in na navpične skoke z dodatnimi bremeni

H_9: hkratna plavalna vadba in vadba moči kot jo prakticirajo plavalni trenerji na pripravah na višini, vpliva na učinkovitost vadbe usmerjene k izboljšanju eksplozivnih gibanj kot sta startni skok in navpični skoki.

Metode

Povzetek uporabljenih metod je prikazan v Tabeli 1, natančnejši opisi pa so podani v besedilu v angleškem jeziku.

Študija	Načrt	Merjenci	Testi	Statistična analiza
I. Predicting vertical jump height from bar velocity	Korelacijska študija	30 plavalcev (23 žensk, 7 moških)	SJ, stopnjevani obremenitveni test	Linearna regresija
II. Comparison of the force-, velocity-, and power-time curves recorded with a force plate and a linear velocity transducer	Korelacijska študija	23 plavalk	SJ stopnjevani obremenitveni test	Dvo- smerna ANOVA, Pearsonova korelacija
III. Relationship between different push–off variables and start performance in experienced swimmers	Korelacijska študija	21 plavalk	Kravlov in delfinov plavalni start	Multipla linearna regresija
IV. The relationship between the lower-body muscular profile and swimming start performance	Korelacijska študija	20 plavalk	Kravlov start, SJ in CMJ, SJ z dodatnimi bremeni, izometrični izteg in upogib kolena	Pearsonov linerni koeficient korelacije
V. Effect of acute exposure to moderate altitude on muscle power: hypobaric hypoxia vs normobaric hypoxia	Primerjalna študija	28 športnikov borilnih športov	Potisk s prsi, stopnjevani obremenitveni test. Hipobarična hipoksije vs normobarična hipoksija	Parni t-test, Wilcoxonov in Mann-Whitney U test

VI. Relationship between vertical jump height and swimming start performance before and after an altitude training camp	Longitudinalna študija	15 plavalcev	SJ stopnjevani obremenitveni test in plavalni start	Dvo- smerna ANOVA, Pearsonova korelacija
VII. The effect of acute and chronic exposure to hypobaric hypoxia on loaded squat jump performance	Longitudinalna študija	16 plavalcev	SJ stopnjevani obremenitveni test	ANOVA
VIII. The maximal mechanical capabilities of leg extensors muscles to generate velocity and power improve at altitude	Primerjalna študija	17 plavalcev (12 žensk, 5 moških)	SJ stopnjevani obremenitveni test, SJ, CMJ	Parni t-test
IX. Relationship between vertical jump height and swimming start performance before and after an altitude training camp	Primerjalna študija	13 plavalcev (8 žensk, 5 moških)	SJ stopnjevani obremenitveni test in kravlov plavalni start	Dvo-smerna ANOVA

Rezultati

Zaradi velikega obsega so rezultati v besedni, tabelarični in grafični obliki predstavljeni samo v glavnem delu naloge v poglavju »results«.

Razprava

Glavne ugotovitve naloge lahko v skladu z devetimi zastavljenimi cilji in prav toliko hipotezami predstavimo v devetih točkah. (I) Iz največje hitrosti gibanja droga pri izvajanju skoka iz počepa v vodilih je možno natančno izračunati višino skoka. (II) Linearni merilnik hitrosti predstavlja veljavno in zanesljivo napravo s katero je mogoče meriti hitrost droga pri navpičnih skokih ali/in potisku iz prsi v vodilih. (III) Izmed spremenljivk merjenih s TP na startnem bloku med plavalnim startnim skokom, vodoravna komponenta odrivne hitrosti predstavlja spremenljivko, ki je najbolj povezana z učinkovitostjo starta, oziroma startnimi časi na 5, 10 in 15 metrov. (IV) Največja hitrost gibanja droga pri izvajanju skokov z dodatnimi bremeni predstavlja spremenljivko, ki najbolje napoveduje uspešnost plavalnega starta. (V) Učinkovitost potiska s prsi in navpičnega skoka se izboljša pri kratkotrajnem (akutnem) bivanju na višini. (VI) Plavalci, ki so dosegali boljše rezultate pri skokih z dodatnimi bremeni (relativnimi glede na njihovo telesno težo) so dosegali tudi boljše startne čase. Prav tako izboljšanje rezultatov navpičnih skokov z dodatnimi bremeni pomeni izboljšanje startnih časov. (VII) Vadba za moč na kopnem, ki se izvaja med bivanjem na zmerni višini, povzroči izboljšanje eksplozivnih gibanj kot so skoki in plavalni start. (VIII) Dvig na zmerno nadmorsko višino povzroči povečanje sposobnosti iztegovalk nog, ki se kaže v povečani mehanski moči in sicer na račun povečane teoretično določene največje hitrosti krčenja, ne pa tudi povečane mišične sile. (IX) Tipičen vadbeni pristop živi visoko – treniraj visoko, v trajanju tri tedne, ki je hkrati orientiran k povečanju moči (vadba na kopnem) in vzdržljivosti (plavalna vadba) bistveno ne vpliva na merjene parametre mišične moči.

I) Tako na podlagi največje hitrosti droga (V_{max}) kot hitrosti v trenutku, ko pospešek postane manjši od gravitacijskega (FPV), je možno izračunati višino navpičnega skoka, vendar je videti kot da je V_{max} malenkost boljši parameter saj smo dosegli višjo napovedno (predikcijsko) vrednost (r^2 = 0.931 vs. 0.913) in manjšo ocenjeno napako merjenja (SEE = 1.47 cm vs. 1.66 cm). Poleg tega je regresijski model za FPV pokazal tendenco podcenjevanja višine skoka pri velikih hitrostih gibanja. Nenazadnje smo ugotovili, da je računanje V_{max} enostavnejše in časovno manj potratno, saj vgrajena programska oprema FPV ne izračuna. Zaradi velike povezanosti z uspešnostjo v športu (Breed & Young, 2003; West et al., 2011) je merjenje navpičnih skokov zelo zanimivo za raziskovalce in trenerje (Naruhiro Hori et al., 2007). Tenziometrijska plošča sicer predstavlja napravo, ki zagotavlja najbolj veljavne in zanesljive rezultate pri merjenju skokov (Linthorne, 2001), vendar pa se izkaže, da so linearni merilniki hitrosti prav tako dovolj zanesljivi, hkrati pa bistveno cenejši in lažje prenosljivi.

II) Rezultati te študije dodatno podpirajo trditve prejšnje, saj je povezanost parametrov, izmerjenih z obema napravama, zelo velika (r = 0.94-0.99 za največjo silo, r = 0.83-0.91 za največjo hitrost in r = 0.90-0.94 za največjo moč ter r = 0.96-0.99 za povprečno silo, r = 0.87-0.89 za povprečno hitrost in r = 0.93-0.96 za povprečno moč). Pri primerjanju krivulj sile, hitrosti in mehanske moči v času med TP in LMH so bile sicer najdene manjše razlike; velikost prirastka omenjenih parametrov je bil na začetku nekoliko večji pri LMH pri izvajanju gibanja z majhno dodatno težo (25 – 50 % TT), pri večjih težah (75 – 100% TT) razlik ni bilo več. Obratno so bile na koncu gibanja vrednosti višje pri TP pri vseh obremenitvah. Rezultati nakazujejo, da se težišče sistema človek – utež z iztegovanjem telesa med skokom spreminja, kar vpliva na parametre izmerjen s TP. Ne glede na višje korelacijske koeficiente smo ugotovili, da je pri parametrih, ki ocenjujejo povprečne vrednosti, večja možnost napake, saj je potrebno arbitrarno določiti trenutek začetka in konca koncentrične faze, kar kaže tudi večji koeficient variabilnosti (CV). Zato v skladu z že objavljenimi študijami, za oceno navpičnih skokov, priporočamo največje vrednosti - največjo silo, hitrost in moč (Dugan et al., 2004; Hori et al., 2007).

III) Različni raziskovalci so za oceno učinkovitosti plavalnega starta uporabili številne parametre. Proti pričakovanjem smo ugotovili, da mnoge spremenljivke, ki jih sicer raziskovalci priporočajo, niso bile povezane z merjenimi startnimi časi na 5, 10 in 15 metrov. Rezultanta odrivne hitrosti in še boljše vodoravna komponenta odrivne hitrosti ter povprečni pospešek v vodoravni smeri so se izkazali za edine spremenljivke, ki so bile značilno povezane z vsemi startnimi časi (na 5, 10 in 15 m). Regresijska analiza je pokazala, da je vodoravna komponenta odrivne hitrosti na startnem bloku tista spremenljivka, ki v največji meri pojasnjuje startne čase, kar je v skladu z nekaterimi prejšnjimi raziskavami (Tor et al., 2015). Največja sila izmerjena med odrivom se v nasprotju z nekaterimi raziskovalci (Kilduff et al., 2011; West et al., 2011), ni pokazala kot parameter povezan s startnimi časi. Zanimiva in pomembna je ugotovitev, da nobeden od parametrov v povezavi z razvijanjem sile na startnem bloku v navpični smeri, ni povezan s startno učinkovitostjo. Plavalci naj se torej usmerijo v razvijanje sile v vodoravni smeri; v tem kontekstu Rebutini (2014) za učinkovitost plavalcev pri startnem skoku, predlaga vadbo vodoravnih in ne navpičnih skokov.

Čas odriva sicer pomembno pojasnjuje uspešnost starta na 5 metrov, vendar je to verjetno posledica tega, da odrivni čas sam po sebi predstavlja pomemben relativni del časa do petih metrov. Po drugi strani krajši odrivni čas pomeni krajše razvijanje sile oziroma manjši sunek sile, ki posledično pomeni manjšo odrivno hitrost in končno slabši startni čas na 15-ih metrih. V tem kontekstu, podobno kot Barlow (2014), ugotavljamo, da morajo plavalci poiskati optimalni čas (ne prekratek in ne predolg) na startnem bloku, končni kazalec uspešnosti pa je čas na 15-ih metrih.

IV) Z učinkovitostjo starta oziroma startnimi časi je bila v največji meri povezana največja hitrost in največja relativna moč (normalizirana na kg telesne teže) izmerjena pri skoku iz počepa (SJ) z dodatnim bremenom. Največja relativna moč in odrivna hitrost pri skoku z nasprotnim gibanjem z lastno telesno težo (CMJ) sta bili povezani s časom na 5 in 10, ne pa tudi na 15 metrov, SJ z lastno težo pa samo s časom na 5 m. Rezultati izometričnih testov (največja sila in prirastek sile) tako upogibalk kot iztegovalk kolena niso bili statistično značilno povezani s startnimi časi. Opazili smo, da se velikost korelacije med SJ in CMJ ter startnimi časi (T) zmanjšuje z razdaljo, kjer so bili merjeni (korelacija s T5 > korelacija s T10 > korelacija s T15), kar je v skladu z ugotovitvami Benjanuvatra et al., 2007). Parametri obeh skokov so bili visoko povezani s T5, T10 je bil zmerno visoko povezan s CMJ, T15 pa s skokoma brez dodatnih bremen ni bil povezan, kar je v nasprotju z West et al. (2011). Razlog za to bi lahko bil v vzorcu, saj so West et al. merili same vrhunske sprinterje, naš vzorec pa je vseboval plavalce in plavalke vseh disciplin, tudi dolgoprogaše. Ugotavljamo torej, da SJ in CMJ ne predstavljata zanesljivega pokazatelja učinkovitega starta do 15 metrov. Ta namreč ni odvisen samo od odriva na startnem bloku ampak tudi od učinkovitega drsenja in plavanja pod vodo do 15 m. Že Jidovtseff et al.(2014) so zaključili, da so športniki pri navpičnih skokih z dodatnim bremenom 20 kg ustvarili večji sunek sile in da lahko pod takšnimi pogoji izboljšamo aktivnosti, kjer je pomemben dober pospešek, kot je npr. odriv.

Čeprav imajo mišice iztegovalke kolena in kolka pomembno vlogi pri navpičnih skokih (Spägele et al., 1999) in pri plavalnem startu (Beretić, Durovic, Okičić, & Dopsaj, 2013), nismo uspeli potrditi značilnih povezav med izometrično močjo teh mišic in startnimi časi. Razlog za to je morda v napačni izbiri izometričnih testov (boljše kot eno-sklepno gibanje bi bilo morda dvo-sklepno), po drugi strani pa so se že prej pojavljala priporočila, naj se za ugotavljanje povezav med relativno močjo in dinamičnimi gibanji uporabljajo dinamični testi (Thomas et al., 2015).

V) Raziskava, kjer je bila preučevana hitrost gibanja droga pri potisku s prsi v vodilih na normalni in zmerni višini je pokazala razlike; pri premagovanju enakega bremena je bila na višini hitrost gibanja droga višja, kot posledica tudi povprečna mehanska moč P_{max} (+3.29%), večje pa je bilo tudi breme, ki so ga merjenci lahko premagali enkrat 1RM (+5.73%) ($P < 0.05$). Prejšnje raziskave so pokazale, da vdihavanje normobaričnega hipoksičnega zraka med vadbo za moč povzroči mišično hipertrofijo (Kon, Ikeda, Homma, & Suzuki, 2012; Nishimura et al., 2010). Scott, Slattery, Sculley, Hodson, & Dascombe (2015) so pokazali, da se trend razvoja sile in moči pri treningu v pogojih normobarične hipoksije in normalnih pogojih ni razlikoval. Po drugi strani je bilo ugotovljeno, da so se na večji nadmorski višini izboljšale kratko trajajoče eksplozivne akcije kot so meti in skoki. (Hamlin et al., 2015; Levine et al., 2008).

Schoenfeld, 2013 navaja, da metabolični stres v obliki povišanja koncentracije H^+ ali zaradi zmanjšanje saturacije O_2 , povzroči povečano rekrutacijo hitrih mišičnih vlaken oziroma zniža prag njihove vzdraženosti.

Žal v raziskavi nismo izvajali potiskov s prsi še na realni višini, torej v pogojih hipobarične hipoksije, kar bi omogočilo bolj poglobljeno razpravo na to temo.

VI) Rezultati te raziskave so pokazali značilno izboljšanje tako plavalnih startnih časov kot skokov iz počepa z dodatnim bremenom (LSJ) po 17-dnevnem treningu mladih vrhunskih plavalcev na višini. Velikost izboljšanja (napredka) obeh parametrov je bila prav tako statistično značilna. V prejšnjih raziskavah je bilo že ugotovljeno, da izboljšanje CMJ ni pomenilo tudi izboljšanja startnega skoka, kar pomeni, da mora biti učinkovita vadba startnega skoka specifična. (Benjanuvatra et al., 2007; Breed & Young, 2003). Zato so v tej študiji mladi plavalci poleg moči vadili tudi tehniko skoka in napredovali tako v višini SJ in startnih časih.

VII) Namen študije je bil ugotoviti ali dvig na zmerno višino vpliva na eksplozivne akcije in ali se nivo sposobnosti po 17- dnevnem bivanju in vadbi na tej višini, spremeni. Analiza je pokazala boljše rezultate LSJ, ko so bili ti izvedeni v hipoksičnih pogojih v primerjavi z normoksičnimi, tako pred vadbo (6,5%) kot po njej (4,5%). Ob predpostavki, da bi morali biti rezultati enaki, lahko 2% razliko pripišemo fiziološkim spremembam, ki bi lahko bili posledica 17-dnevnega bivanja na višini. Rezultati se skladajo z ugotovitvami drugih avtorjev, ki so ugotovili, da se rezultati anaerobnih eksplozivnih gibanj na višini izboljšajo (Hahn and Gore, 2001; Kenney et al., 2012; Levine et al., 2008). Izmed 16 plavalcev sta samo dva (eden na testu pred vadbo in drugi po vadbi) imela boljše rezultate v pogojih normobarične normoksije, vsi ostali pa v pogojih hipobarične hipoksije. Ti rezultati nakazujejo, da izpostavljenost in vadba na višini verjetno pozitivno vpliva na eksplozivna gibanja.

VIII) Glavna ugotovitev raziskave je bila, da je kratkotrajna izpostavljenost zmerni višini povzročila povišanje največje teoretične (izračunane) hitrosti V_0 in moči P_0, ne pa tudi sile F_0, v primerjavi z vrednostmi izmerjenimi na nizki normalni višini pred dvigom. Prav tako so bile višje največje izmerjene vrednosti sile, moči in višine skokov, predvsem pri skoku z nasprotnim gibanjem (CMJ). Dvig na zmerno nadmorsko višino torej vpliva na odnos sila-hitrost izmerjenem s skoki z dodatnimi bremeni. Vpliv višine na hitrost in moč (na račun hitrosti), ne pa tudi na največjo silo, sugerira, da je povečana višina primerno vadbeno okolje za razvoj hitrih gibov kot so teniški udarec, met žoge ali kopja, odbojkarski udarec ipd.)

Razlike med izvedbo na nizki in zmerni nadmorski višini smo našli tudi pri parametrih navpičnih skokov, tako SJ kot CMJ. Meritve so bile izvedene s tenziometrijsko ploščo, kar pomeni, da smo z neposrednim merjenjem sile reakcije podlage in s tem nasprotno enake sile iztegovalk nog, izločili potencialni vpliv zmanjšane gostote zraka na merjene parametre. Višje vrednosti merjenih parametrov nakazujejo, da se živčno-mišična funkcija na zmerni višini v primerjavi z nizko nadmorsko višino dejansko izboljša.

IX) Namen študije je bil primerjati vadbo v dveh tri-tedenskih pripravljalnih obdobjih (v istem času leta in istem obdobju tekmovalnega makro ciklusa) pri vrhunskih plavalcih, dve leti zapored, pri čemer je bila vadba v prvem letu izvedena na nizki nadmorski višini, vadba v drugem letu pa na zmerni (2320 m) nadmorski višini. Vadba v obeh pogojih je povzročila podobne majhne spremembe obravnavanih spremenljivk. Glede na to, da je vadba na zmerni višini napornejša od vadbe na nizki višini, lahko rečemo vsaj to, da intenzivna plavalna (pretežno vzdržljivostno usmerjena) vadba na višini ni poslabšala učinkov vadbe moči na kopnem, kar se sicer pogosto lahko zgodi (Rønnestad et al., 2012). Tudi Häkkinen et al.(2013) so poročali, da vzporedna oziroma hkratna vadba moči in vzdržljivostna vadba zmanjšuje pričakovani napredek vadbe hitre moči. Vadba moči na zmerni višini na kopnem ob vzporedni obsežni vzdržljivostni plavalni vadbi, ne vpliva na povečanje parametrov hitre moči, vendar jih vsaj ohranja. Glede na ugotovitve prejšnjih raziskav bi bilo namreč pričakovati, da se bo hitra moč ob obsežnem vzdržljivostnem treningu, lahko tudi zmanjšala.

REFERENCES

Aeberli, I., Erb, A., Spliethoff, K., Meier, D., Gotze, O., Fruhauf, H., … Lutz, T. A. (2013). Disturbed eating at high altitude: influence of food preferences, acute mountain sickness and satiation hormones. *European Journal of Nutrition*, *52*(2), 625–635. http://doi.org/10.1007/s00394-012-0366-9

Arellano, R., Brown, P., Cappaert, J., & Nelson, R. C. (1994). Analysis of 50- , 100- , and 200-m freestyle swimmers at the 1992 Olympic Games. *Journal of Applied Biomechanics*, *10*, 189–199.

Baker, D., Wilson, G., & Carlyon, B. (1994). Generality versus specificity: a comparison of dynamic and isometric measures of strength and speed-strength. *European Journal of Applied Physiology and Occupational Physiology*, *68*(4), 350–355. http://doi.org/10.1007/BF00571456

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 15 m in developmental level swimmers. *Human Movement Science*, *34*, 178–186. http://doi.org/10.1016/j.humov.2014.02.002

Benjanuvatra, N., Edmunds, K., & Blanksby, B. (2007). Jumping ability and swimming grab-start performance in elite and recreational swimmers. *International Journal of Aquatic Research and Education*, *1*, 231–241.

Beretić, I., Durovic, M., Okičić, T., & Dopsaj, M. (2013). Relations between lower body isometric muscle force characteristics and start performance in elite male sprint swimmers. *Journal of Sports Science and Medicine*, *12*(4), 639–645.

Bishop, C., Cree, J., Read, P., Chavda, S., Edwards, M., & Turner, A. (2013). Strength and conditioning for sprint swimming. *Strength and Conditioning Journal*, *35*(6), 1–6. http://doi.org/10.1519/SSC.0000000000000019

Bishop, D. C., Smith, R. J., Smith, M. F., & Rigby, H. E. (2009). Effect of plyometric training on swimming block start performance in adolescents. *Journal of Strength and Conditioning Research*, *23*(7), 2137–2143. http://doi.org/10.1519/JSC.0b013e3181b866d0

Bonetti, D. L., & Hopkins, W. G. (2009). Sea-level exercise performance following adaptation to hypoxia: a meta-analysis. *Sports Medicine*. http://doi.org/10.2165/00007256-200939020-00002

Borg, G., Ljunggren, G., & Ceci, R. (1985). The increase of perceived exertion, aches and pain in the legs, heart rate and blood lactate during exercise on a bicycle ergometer. *European Journal of Applied Physiology and Occupational Physiology*, *54*(4), 343–349. http://doi.org/10.1007/BF02337176

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. http://doi.org/10.1080/0264041031000071047

Chirosa, I., Feriche, B., Calderón, C., Martínez, M., Braga, R., & Padial, P. (2006). Ascent to moderate altitude improves force production. *Archivos de Medicina Del Deporte*, *23*, 101–108.

Chiu, L. Z. F., Fry, A. C., Weiss, L. W., Schilling, B. K., Brown, L. E., & Smith, S. L. (2003). Postactivation potentiation response in athletic and recreationally trained individuals. *Journal of Strength and Conditioning Research / National Strength & Conditioning Association*, *17*(4), 671–677. http://doi.org/10.1519/1533-4287(2003)017<0671:PPRIAA>2.0.CO;2

Cormie, P., Deane, R., & McBride, J. M. (2007). Methodological concerns for determining power output in the jump squat. *Journal of Strength & Conditioning Research*, *21*(2), 424–430. http://doi.org/10.1519/r-19605.1

Cormie, P., McBride, J. M., & McCaulley, G. O. (2007). Validation of power measurement techniques in dynamic lower body resistance exercises. *Journal of Applied Biomechanics*, *23*(2), 103–118.

Cormie, P., McBride, J. M., & McCaulley, G. O. (2009). Power-time, force-time, and velocity-time curve analysis of the countermovement jump: impact of training. *Journal of Strength and Conditioning Research / National Strength & Conditioning Association*, *23*(1), 177–186. http://doi.org/10.1519/JSC.0b013e3181889324

Cormie, P., McGuigan, M. R., & Newton, R. U. (2010). Adaptations in athletic performance after ballistic power versus strength training. *Medicine and Science in Sports and Exercise*, *42*(8), 1582–1598. http://doi.org/10.1249/MSS.0b013e3181d2013a

Crewther, B. T., Kilduff, L. P., Cunningham, D. J., Cook, C., Owen, N., & Yang, G. Z. (2011). Validating two systems for estimating force and power. *International Journal of Sports Medicine*, *32*(4), 254–258. http://doi.org/10.1055/s-0030-1270487

Cronin, J. B., Hing, R. D., & McNair, P. J. (2004). Reliability and validity of a linear position transducer for measuring jump performance. *Journal of Strength and Conditioning Research*, *18*(3), 590–593. http://doi.org/10.1519/1533-4287(2004)18<590:RAVOAL>2.0.CO;2

Cuk, I., Markovic, M., Nedeljkovic, A., Ugarkovic, D., Kukolj, M., & Jaric, S. (2014). Force-velocity relationship of leg extensors obtained from loaded and unloaded vertical jumps. *European Journal of Applied Physiology*, *114*(8), 1703–1714. http://doi.org/10.1007/s00421-014-2901-2

De la Fuente, B., García, F., & Arellano, R. (2003). Are the forces applied in the vertical countermovement jump related to the forces applied during the swimming start? In *IXth* *international symposium on biomechanics and medicine in swimming* (pp. 207–212). University of Saint-Etienne, France.

Deldicque, L., & Francaux, M. (2013). Acute vs chronic hypoxia: what are the consequences for skeletal muscle mass? *Cellular and Molecular Exercise Physiology*, *2*(1), e5. http://doi.org/10.7457/cmep.v2i1.e5

Dugan, E. L., Doyle, T. L. A., Humphries, B., Hasson, C. J., & Newton, R. U. (2004). Determining the optimal load for jump squats: a review of methods and calculations. *Journal of Strength and Conditioning Research*, *18*(3), 668–674. http://doi.org/10.1519/1533-4287(2004)18<668:DTOLFJ>2.0.CO;2

Elipot, M., Hellard, P., Taïar, R., Boissière, E., Rey, J. L., Lecat, S., & Houel, N. (2009). Analysis of swimmers' velocity during the underwater gliding motion following grab start. *Journal of Biomechanics*, *42*(9), 1367–1370. http://doi.org/10.1016/j.jbiomech.2009.03.032

Etheridge, T., Atherton, P. J., Wilkinson, D., Selby, A., Rankin, D., Webborn, N., … Watt, P. W. (2011). Effects of hypoxia on muscle protein synthesis and anabolic signaling at rest and in response to acute resistance exercise. *AJP: Endocrinology and Metabolism*. http://doi.org/10.1152/ajpendo.00276.2011

Felici, F., Rosponi, A., Sbriccoli, P., Scarcia, M., Bazzucchi, I., & Iannattone, M. (2001). Effect of human exposure to altitude on muscle endurance during isometric contractions. *European Journal of Applied Physiology*, *85*(6), 507–512.

Feriche, B., García-Ramos, A., Calderón-Soto, C., Drobnic, F., Bonitch-Góngora, J. G., Galilea, P. A., … Padial, P. (2014). Effect of acute exposure to moderate altitude on muscle power: hypobaric hypoxia vs. normobaric hypoxia. *PLoS ONE*, *9*(12), e114072. http://doi.org/10.1371/journal.pone.0114072

Ferretti, G., Hauser, H., & di Prampero, P. E. (1990). Maximal muscular power before and after exposure to chronic hypoxia. *International Journal of Sports Medicine*, *11 Suppl 1*, S31–S34. http://doi.org/10.1055/s-2007-1024851

Friedmann, B., Frese, F., Menold, E., Kauper, F., Jost, J., & Bartsch, P. (2005). Individual variation in the erythropoietic response to altitude training in elite junior swimmers. *British Journal of Sports Medicine*, *39*(3), 148–153. http://doi.org/10.1136/bjsm.2003.011387

Fulco, C. S., Friedlander, A. L., Muza, S. R., Rock, P. B., Robinson, S., Lammi, E., … Cymerman, A. (2002). Energy intake deficit and physical performance at altitude. *Aviation Space and Environmental Medicine*, *73*(8), 758–765.

García-Ramos, A., Argüelles, J., de la Fuente, B., Padial, P., Bonitch, J., Calderón, C., & Feriche, B. (2014). Performance of muscular power profile after a training camp at moderate natural altitude in young swimmers. *Journal of Strength and Conditioning Research*, *28*(11), 85.

García-Ramos, A., Feriche, B., De la Fuente, B., Argüelles-Cienfuegos, J., Strojnik, V., Strumbelj, B., & Stirn, I. (2015). Relationship between different push–off variables and start performance in experienced swimmers. *European Journal of Sport Science*, *15*(8), 687–695.

Garcia-Ramos, A., Jaric, S., Padial, P., & Feriche, B. (2016). Force-velocity relationship of upper-body muscles: traditional vs. ballistic bench press. *Journal of Applied Biomechanics*, *32*(2), 178–185. http://doi.org/10.1123/jab.2015-0162

García-Ramos, A., Štirn, I., Padial, P., Argüelles-Cienfuegos, J., De la Fuente, B., Strojnik, V., & Feriche, B. (2015). Predicting vertical jump height from bar velocity. *Journal of Sports Science and Medicine*, *14*, 256–262.

Giroux, C., Rabita, G., Chollet, D., & Guilhem, G. (2015). What is the best method for assessing lower limb force-velocity relationship? *International Journal of Sports*

Medicine, *36*(2), 143–149. http://doi.org/10.1055/s-0034-1385886

González-Badillo, J. J., Marques, M. C., & Sánchez-Medina, L. (2011). The Importance of Movement Velocity as a Measure to Control Resistance Training Intensity. *Journal of Human Kinetics*. http://doi.org/10.2478/v10078-011-0053-6

Govus, A. D., Garvican-Lewis, L. A., Abbiss, C. R., Peeling, P., & Gore, C. J. (2015). Pre-Altitude Serum Ferritin Levels and Daily Oral Iron Supplement Dose Mediate Iron Parameter and Hemoglobin Mass Responses to Altitude Exposure. *PloS One*, *10*(8), e0135120. http://doi.org/10.1371/journal.pone.0135120

Hahn, A. G., & Gore, C. J. (2001). The effect of altitude on cycling performance: a challenge to traditional concepts. *Sports Medicine (Auckland, N.Z.)*, *31*(7), 533–557.

Hainsworth, R., Drinkhill, M. J., & Rivera-Chira, M. (2007). The autonomic nervous system at high altitude. *Clinical Autonomic Research : Official Journal of the Clinical Autonomic Research Society*, *17*(1), 13–19. http://doi.org/10.1007/s10286-006-0395-7

Häkkinen, K., Alen, M., Kraemer, W. J., Gorostiaga, E., Izquierdo, M., Rusko, H., … Paavolainen, L. (2003). Neuromuscular adaptations during concurrent strength and endurance training versus strength training. *European Journal of Applied Physiology*, *89*(1), 42–52. http://doi.org/10.1007/s00421-002-0751-9

Hamlin, M. J., Hopkins, W. G., & Hollings, S. C. (2015). Effects of altitude on performance of elite track-and-field athletes. *International Journal of Sports Physiology and Performance*, *10*(7), 881–887. http://doi.org/10.1123/ijspp.2014-0261

Harman, E. A., Rosenstein, M. T., Frykman, P. N., & Rosenstein, R. M. (1990). The effects of arms and countermovement on vertical jumping. *Medicine and Science in Sports and Exercise*, *22*(6), 825–833. http://doi.org/10.1519/0744-0049(1991)013<0038:TEOAAC>2.3.CO;2

Harris, N. K., Cronin, J., Taylor, K. L., Boris, J., & Sheppard, J. (2010). Understanding position transducer technology for strength and conditioning practitioners. *Strength and Conditioning Journal*, *32*(4), 66–79. http://doi.org/10.1519/SSC.0b013e3181eb341b

Hopkins, W. (2002). A scale of magnitudes for effect statistics. A new view of statistics. Retrieved from http://sportsci.org/resource/stats/effectmag.html

Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine and Science in Sports and Exercise*, *41*(1), 3–13. http://doi.org/10.1249/MSS.0b013e31818cb278

Hoppeler, H., & Desplanches, D. (1992). Muscle structural modifications in hypoxia. *International Journal of Sports Medicine*, *13*(Suppl 1), S166–S168. http://doi.org/10.1055/s-2007-1024628

Hori, N., Newton, R. U., Andrews, W. A., Kawamori, N., McGuigan, M. R., & Nosaka, K. (2007). Comparison of four different methods to measure power output during the hang power clean and the weighted jump squat. *Journal of Strength and Conditioning Research*, *21*(2), 314–320. http://doi.org/10.1519/R-22896.1

Hori, N., Newton, R. U., Nosaka, K., & McGuigan, M. (2006). Comparison of different methods of determining power output in weightlifting exercises. *Strength and Conditioning Journal*, *28*(2), 34–40. Retrieved from <Go to ISI>://WOS:000236955800006

Jaric, S. (2015). Force-velocity relationship of muscles performing multi-joint maximum performance tasks. *International Journal of Sports Medicine*, *36*(9), 699–704. http://doi.org/10.1055/s-0035-1547283

Jidovtseff, B., Quievre, J., Harris, N. K., & Cronin, J. B. (2014). Influence of jumping strategy on kinetic and kinematic variables. *Journal of Sports Medicine and Physical Fitness*, *54*(2), 129–138.

Jiménez-Reyes, P., Samozino, P., Cuadrado-Peñafiel, V., Conceição, F., González-Badillo, J.

J., & Morin, J. B. (2014). Effect of countermovement on power-force-velocity profile. *European Journal of Applied Physiology*, *114*(11), 2281–2288. http://doi.org/10.1007/s00421-014-2947-1

Kenney, W., Wilmore, J., & Costill, D. (2012). *Physiology of Sport and Exercise*. Human Kinetics.

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. *Journal of Strength and Conditioning Research / National Strength & Conditioning Association*, *25*(9), 2418–23. http://doi.org/10.1519/JSC.0b013e318201bf7a

Kon, M., Ikeda, T., Homma, T., & Suzuki, Y. (2012). Effects of low-intensity resistance exercise under acute systemic hypoxia on hormonal responses. *Journal of Strength and Conditioning Research / National Strength & Conditioning Association*, *26*(3), 611–617. http://doi.org/10.1519/JSC.0b013e3182281c69

Lake, J. P., Lauder, M. A., & Smith, N. A. (2012). Barbell kinematics should not be used to estimate power output applied to the Barbell-and-body system center of mass during lower-body resistance exercise. *Journal of Strength and Conditioning Research*, *26*(5), 1302–1307. http://doi.org/10.1519/JSC.0b013e31822e7b48

Levine, B. D., Stray-Gundersen, J., & Mehta, R. D. (2008). Effect of altitude on football performance. *Scandinavian Journal of Medicine & Science in Sports*, *18 Suppl 1*, 76–84. http://doi.org/10.1519/JSC.0b013e31825d999d

Li, L., Olson, M. W., & Winchester, J. B. (2008). A proposed method for determining peak power in the jump squat exercise. *Journal of Strength and Conditioning Research / National Strength & Conditioning Association*, *22*(2), 326–331. http://doi.org/10.1519/JSC.0b013e3181635606

Linthorne, N. P. (2001). Analysis of standing vertical jumps using a force platform. *American Journal of Physics*, *69*(11), 1198–1204.

Manimmanakorn, A., Manimmanakorn, N., Taylor, R., Draper, N., Billaut, F., Shearman, J. P., & Hamlin, M. J. (2013). Effects of resistance training combined with vascular occlusion or hypoxia on neuromuscular function in athletes. *European Journal of Applied Physiology*, *113*(7), 1767–1774. http://doi.org/10.1007/s00421-013-2605-z

Markovic, G., & Jaric, S. (2007). Is vertical jump height a body-size independent measure of muscle power? *Journal of Sports Sciences*, *25*(12), 1355–1363.

Mason, B., & Cossor, J. (2000). What can we learn from competition analysis at the 1999 Pan Pacific swimming championships? In Y. (ed. . In Sanders, R. and Hong (Ed.), *Proceedings of XVIII International Symposium on Biomechanics in Sports – Applied Program.* (pp. 75–82). Hong Kong: Chinese University Press.

McBride, J. M., Haines, T. L., & Kirby, T. J. (2011). Effect of loading on peak power of the bar, body, and system during power cleans, squats, and jump squats. *Journal of Sports Sciences*, *29*(11), 1215–1221. http://doi.org/10.1080/02640414.2011.587444

McMaster, D. T., Gill, N., Cronin, J., & McGuigan, M. (2014). A brief review of strength and ballistic assessment methodologies in sport. *Sports Medicine*, *44*(5), 603–623. http://doi.org/10.1007/s40279-014-0145-2

Meylan, C., Cronin, J., Oliver, J., Hughes, M., Jidovtseff, B., & Pinder, S. (2015). The reliability of isoinertial force–velocity–power profiling and maximal strength assessment in youth. *Sports Biomechanics*, *14*(1), 68–80. http://doi.org/10.1080/14763141.2014.982696

Mizuno, M., Savard, G. K., Areskog, N. H., Lundby, C., & Saltin, B. (2008). Skeletal muscle adaptations to prolonged exposure to extreme altitude: a role of physical activity? *High Altitude Medicine & Biology*, *9*(4), 311–317. http://doi.org/10.1089/ham.2008.1009

Narici, M. V, & Kayser, B. (1995). Hypertrophic response of human skeletal muscle to strength training in hypoxia and normoxia. *European Journal of Applied Physiology and Occupational Physiology*, *70*(3), 213–219. http://doi.org/10.1007/BF00238566

Newton, R. U., Kraemer, W. J., & Häkkinen, K. (1999). Effects of ballistic training on preseason preparation of elite volleyball players. *Medicine and Science in Sports and Exercise*, *31*(2), 323–330. http://doi.org/10.1097/00005768-199902000-00017

Nikolaidis, P. (2012). Age- and sex-related differences in force-velocity characteristics of upper and lower limbs of competitive adolescent swimmers. *Journal of Human Kinetics*, *32*, 87–95. http://doi.org/10.2478/v10078-012-0026-4

Nishimura, A., Sugita, M., Kato, K., Fukuda, A., Sudo, A., & Uchida, A. (2010). Hypoxia increases muscle hypertrophy induced by resistance training. *International Journal of Sports Physiology and Performance*, *5*(4), 497–508.

Peronnet, F., Thibault, G., & Cousineau, D. L. (1991). A theoretical analysis of the effect of altitude on running performance. *J Appl Physiol*, *70*(1), 399–404.

Raguso, C. A., Guinot, S. L., Janssens, J.-P., Kayser, B., & Pichard, C. (2004). Chronic hypoxia: common traits between chronic obstructive pulmonary disease and altitude. *Current Opinion in Clinical Nutrition and Metabolic Care*, *7*(4), 411–417.

Rebutini, V. Z., Pereira, G., Bohrer, R. C. D., Ugrinowitsch, C., & Rodacki, A. L. F. (2014). Plyometric long jump training with progressive loading improves kinetic and kinematic swimming start parameters. *Journal of Strength and Conditioning Research*. http://doi.org/10.1519/JSC.0000000000000360

Rodriguez, F. A., Iglesias, X., Feriche, B., Calderon-Soto, C., Chaverri, D., Wachsmuth, N. B., … Levine, B. D. (2015). Altitude Training in Elite Swimmers for Sea Level Performance (Altitude Project). *Medicine and Science in Sports and Exercise*, *47*(9), 1965–1978. http://doi.org/10.1249/MSS.0000000000000626

Rønnestad, B. R., Hansen, E. A., & Raastad, T. (2012). High volume of endurance training impairs adaptations to 12 weeks of strength training in well-trained endurance athletes. *European Journal of Applied Physiology*, *112*, 1457–1466. http://doi.org/10.1007/s00421-011-2112-z

Samozino, P., Edouard, P., Sangnier, S., Brughelli, M., Gimenez, P., & Morin, J. B. (2014). Force-velocity profile: Imbalance determination and effect on lower limb ballistic performance. *International Journal of Sports Medicine*, *35*(6), 505–510. http://doi.org/10.1055/s-0033-1354382

Samozino, P., Rejc, E., Di Prampero, P. E., Belli, A., & Morin, J. B. (2012). Optimal force-velocity profile in ballistic movements-Altius: Citius or Fortius? *Medicine and Science in Sports and Exercise*, *44*(2), 313–322. http://doi.org/10.1249/MSS.0b013e31822d757a

Sánchez-Medina, L., & González-Badillo, J. J. (2011). Velocity loss as an indicator of neuromuscular fatigue during resistance training. *Medicine & Science in Sports & Exercise*, *43*(9), 1725–1734. http://doi.org/10.1249/MSS.0b013e318213f880

Sánchez-Medina, L., González-Badillo, J. J., Pérez, C. E., & Pallarés, J. G. (2014). Velocity- and power-load relationships of the bench pull vs bench press exercises. *International Journal of Sports Medicine*, *35*(3), 209–216. http://doi.org/10.1055/s-0033-1351252

Sanchez-Medina, L., Perez, C. E., & Gonzalez-Badillo, J. J. (2010). Importance of the propulsive phase in strength assessment. *International Journal of Sports Medicine*, *31*(2), 123–129. http://doi.org/10.1055/s-0029-1242815

Schoenfeld, B. J. (2013). Potential mechanisms for a role of metabolic stress in hypertrophic adaptations to resistance training. *Sports Medicine*. http://doi.org/10.1007/s40279-013-0017-1

Scott, B. R., Slattery, K. M., Sculley, D. V, Hodson, J. A., & Dascombe, B. J. (2015). Physical performance during high-intensity resistance exercise in normoxic and hypoxic conditions. *Journal of Strength and Conditioning Research / National Strength & Conditioning Association*, *29*(3), 807–815. http://doi.org/10.1519/JSC.0000000000000680

Seifert, L., Vantorre, J., Lemaitre, F., Chollet, D., Toussaint, H. M., & Vilas-Boas, J.-P. (2010). Different profiles of the aerial start phase in front crawl. *Journal of Strength and Conditioning Research*, *24*(2), 507–516. http://doi.org/10.1519/JSC.0b013e3181c06a0e

Slawson, S. E., Conway, P. P., Cossor, J., Chakravorti, N., & West, A. 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*(April 2016), 468–78. http://doi.org/10.1080/02640414.2012.736631

Sleivert, G., & Taingahue, M. (2004). The relationship between maximal jump-squat power and sprint acceleration in athletes. *European Journal of Applied Physiology*, *91*(1), 46–52. http://doi.org/10.1007/s00421-003-0941-0

Spägele, T., Kistner, A., & Gollhofer, A. (1999). Modelling, simulation and optimisation of a human vertical jump. *Journal of Biomechanics*, *32*(5), 521–530. http://doi.org/10.1016/S0021-9290(98)00145-6

Sreckovic, S., Cuk, I., Djuric, S., Nedeljkovic, A., Mirkov, D., & Jaric, S. (2015). Evaluation of force-velocity and power-velocity relationship of arm muscles. *European Journal of Applied Physiology*, *115*(8), 1779–1787. http://doi.org/10.1007/s00421-015-3165-1

Thomas, C., Jones, P. A., Rothwell, J., Chiang, C.-Y., & Comfort, P. (2015). An investigation into the relationship between maximum isometric strength and vertical jump performance. *Journal of Strength and Conditioning Research*, *29*(8), 2176–2185. http://doi.org/10.1519/JSC.0000000000000866

Tomazin, K., Dolenec, A., & Strojnik, V. (2008). High-frequency fatigue after alpine slalom skiing. *European Journal of Applied Physiology*, *103*(2), 189–194.

http://doi.org/10.1007/s00421-008-0685-y

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. http://doi.org/10.1080/02640414.2014.990486

Tor, E., Pease, D. L., Ball, K. A., & Hopkins, W. G. (2014). Monitoring the effect of race-analysis parameters on performance in elite swimmers. *International Journal of Sports Physiology and Performance*, *9*(4), 633–636. http://doi.org/10.1123/ijspp.2013-0205

Umberger, B. (1998). Mechanics of the vertical jump and two-joint muscles: implications for training. *Strength and Conditioning Journal*, *20*(5), 70–74.

Vuk, S., Markovic, G., & Jaric, S. (2012). External loading and maximum dynamic output in vertical jumping: the role of training history. *Human Movement Science*, *31*(1), 139–151. http://doi.org/10.1016/j.humov.2011.04.007

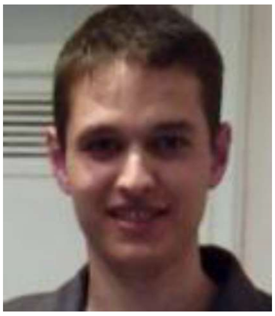
West, D. J., Owen, N. J., Cunningham, D. J., Cook, C. J., & Kilduff, L. P. (2011). Strength and power predictors of swimming starts in international sprint swimmers. *Journal of Strength and Conditioning Research*, *25*(4), 950–955. http://doi.org/10.1519/JSC.0b013e3181c8656f

Wilber, R. L., Stray-Gundersen, J., & Levine, B. D. (2007). Effect of hypoxic "dose" on physiological responses and sea-level performance. *Medicine and Science in Sports and Exercise*, *39*, 1590–1599. http://doi.org/10.1249/mss.0b013e3180de49bd

Zatsiorsky, V., Bulgakova, N., & Chaplinsky, N. (1979). Biomechanical analysis of starting techniques in swimming. In I. J. T. and E. W. B. (Eds.) (Ed.), *Swimming III* (pp. 199–206). University Park Press, Baltimore.

SHORT CV

PERSONAL DATA



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EDUCATION

2007-2011	Bachelor of Science in Physical Activity and Sport.
2011-2012	Master of Research in Physical Activity and Sport.
2012-2013	Master of Education in Teaching. Specialty in Physical Education.
2012 to present	Doctoral Program in Biomedicine. University of Granada.
2014 to present	Doctoral Program in Kinesiology. University of Ljubljana.

RESEARCH STAYS

1. High Performance Center of Sierra Nevada, Spain. 47 days.
2. National Institute for Physical Education of Catalonia, Spain. 60 days.
3. Catholic University of Valencia San Vicente Mártir, Spain. 31 days.
4. Faculty of Sport of Ljubljana, Slovenia. 184 days.

RESEARCH PROJECTS

1. Efecto del tiempo de permanencia y de la estrategia de entrenamiento en altitud (HiHi vs Hi Lo) y sobre el rendimiento, la técnica y el estado de salud en nadadores de élite. (Ayuda complementaria al proyecto ALTITUDE) (CAR 2011-02). Consejo Superior de Deportes. Centro de Alto Rendimiento de Sierra Nevada.

2. Efectos de distintas estrategias de entrenamiento en altitud sobre el rendimiento, la técnica y el estado de salud en deportistas de élite (proyecto ALTITUDE) (112/UPB/12). Consejo Superior de Deportes.

3. Efecto del ascenso a la altura moderada sobre el comportamiento muscular en diferentes manifestaciones de fuerza y su vinculación al rendimiento en nadadores experimentados (DEP2012-35774). Ministerio de economía y competitividad. Subprograma de proyectos de investigación fundamental con orientada. Convocatoria 2012. Plan Nacional de I+D+i (2008-2011)

4. Influencia de la estrategia de exposición a la hipixia moderada sobre las adaptaciones al entrenamiento de la potencia muscular (DEP2015-64350-P). Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia. Subprograma Estatal de Generación de Conocimiento. Proyectos I+D 2015.

UNIVERSITY TEACHING

2014-2015 Professor in "Sport Training" subject, Degree in Physical Activity and Sport, University of Granada (6 credits).

2015-2016 Professor in "Sport Training" subject, Degree in Physical Activity and Sport, University of Granada (6 credits).

SCIENTIFIC PUBLICATIONS

The doctoral student has published 15 articles in scientific journals indexed in JCR (Journal Citation Reports) and has presented 16 abstract in scientific congresses. These publications have received 24 citations from 2014 and the h index of the doctoral student is 3 (based on Google Scholar).

Scientific Publications derived from the present Doctoral Thesis:

1. **García-Ramos, A.**, Štirn, I., Padial, P., Argüelles-Cienfuegos, J., De la Fuente, B., Strojnik, V., & Feriche, B. (2015). Predicting vertical jump height from bar velocity. Journal of Sports Science and Medicine, 14(2), 256–262.

2. **García-Ramos, A.**, Štirn, I., Strojnik, V., Padial, P., De la Fuente, B., Argüelles-Cienfuegos, J., & Feriche, B. (2016). Comparison of the force-, velocity-, and power-time curves recorded with a force plate and a linear velocity transducer. Sports Biomechanics, [Epub ahead of print].

3. **García-Ramos, A.**, Feriche, B., de la Fuente, B., Argüelles-Cienfuegos, J., Strojnik, V., Strumbelj, B., and Štirn, I. (2015). Relationship between different push–off variables and start performance in experienced swimmers. European Journal of Sport Science, 15(8), 687–695.

4. **García-Ramos, A.**, Tomazin, K., Feriche, B., Strojnik, V., de la Fuente, B., Argüelles-Cienfuegos, J., Strumbelj, B., and Štirn, I. (2015). The relationship between the lower-body muscular profile and swimming start performance. Journal of Human Kinetics, 46, 149–156.

5. Feriche, B., **García-Ramos, A**., Calderón, C., Drobnic, F., Bonitch-Gongora, J. G., Galilea, P. A., Riera, J., & Padial, P. (2014). Effect of acute exposure to moderate altitude on muscle power: hypobaric hypoxia vs normobaric hypoxia. PLoS ONE, 9 (12), e114072. DOI: 10.1371/journal.pone.0114072.

6. **García-Ramos, A.**, Padial, P., de la Fuente, B., Argüelles, J., Bonitch-Góngora, J., & Feriche, B. Relationship between vertical jump height and swimming start performance before and after an altitude training camp, Journal of Strength and Conditioning Research, Epub ahead of print.

Other scientific publications:

1. **García-Ramos, A.**, Feriche, B., Calderón, C., Iglesias, X., Barrero, A., Chaverri, D., Schuller, T., & Rodríguez, F. A.. (2015). Training load quantification in elite swimmers using a modified version of the training impulse method. European Journal of Sport Science, 15 (2), 85–93. DOI: 10.1080/17461391.2014.922621.

2. Gómez-Hervás, J., García-Valdecasas Bernal, J., Fernández-Prada, M., Palomeque-Vera, J. M., **García-Ramos, A.**, & Feriche, B. (2015). Effects of oxymetazoline on nasal flow and maximum aerobic exercise performance in patients with inferior turbinate hypertrophy. The Laryngoscope, 125 (6), 1301–1306. DOI: 10.1002/lary.25107.

3. **García-Ramos, A.**, Padial, P., Haff, G. G., Argüelles-Cienfuegos, J., García-Ramos, M., Conde-Pipó, J., & Feriche, B. (2015). Effect of different inter-repetition rest periods on barbell velocity loss during the ballistic bench press exercise. Journal of Strength and Conditioning Research, 29(9), 2388– 2396.

4. Bazuelo-Ruiz, B., Padial, P., **García-Ramos, A.**, Morales-Artacho, A. J., Miranda, M. T., & Feriche, B. (2015). Predicting maximal dynamic strength from the load-velocity relationship in squat exercise. Journal of Strength and Conditioning Research, 29(7), 1999–2005.

5. Morales-Artacho, A. J., Padial, P., **García-Ramos, A.**, & Feriche, B. (2015). The Effect of the number of sets on power output for different loads. Journal of Human Kinetics, 46, 149–156.

6. **García-Ramos, A.**, Padial, P., García-Ramos, M., Conde-Pipó, J., Argüelles-Cienfuegos, J., Štirn, I., and Feriche, B. Reliability analysis of traditional and ballistic bench press exercises at different loads. Journal of Human Kinetics, 47, 51–59.

7. Morales-Artacho, A. J., Padial, P., Rodríguez-Matoso, D., Rodríguez-Ruiz, D., **García-Ramos, A.**, García-Manso, J., Calderón, C., & Feriche, B. Assessment of muscle contractile

properties at acute moderate altitude through tensiomyography. High altitude Medicine and Biology, [epub ahead of print].

8. **García-Ramos, A.**, Slobodan, J., Padial, P., & Feriche, B. Force–velocity relationship of upper-body muscles: traditional vs. ballistic bench press. Journal of Applied Biomechanics, 32(2), 178–185.

9. **García-Ramos, A.**, Haff, G. G., Padial, P., & Feriche, B. Optimal load for maximizing upper-body power: test-retest reproducibility. Isokinetics and Exercise Science, [epub ahead of print].