Programa de doctorado en Biomedicina

Universidad de Granada

# The influence of moderate hypobaric hypoxia on power oriented resistance training

## Influencia de la hipoxia moderada sobre la potencia máxima y su entrenamiento

*Author:*
Antonio J. Morales Artacho

*Supervisor:*
Dr. Belén Feriche

February, 2019

Editor: Universidad de Granada. Tesis Doctorales
Autor: Antonio Jesús Morales Artacho
ISBN: 978-84-1306-157-3
URI: http://hdl.handle.net/10481/55484

MARÍA BELÉN FERICHE FERNÁNDEZ-CASTANYS, CATEDRÁTICA DE LA UNIVERSIDAD DE GRANADA

CERTIFICA:

Que la Tesis Doctoral titulada "Influencia de la hipoxia moderada sobre la potencia máxima y su entrenamiento" que presenta D. **Antonio Jesús Morales Artacho** al superior juicio del Tribunal que designe la Universidad de Granada, ha sido realizada bajo mi dirección durante los años 2014-2018, siendo expresión de la capacidad técnica e interpretativa de su autor en condiciones tan aventajadas que le hacen merecedor del Título de Doctor, siempre y cuando así lo considere el citado Tribunal.

Fdo. M. Belén Feriche Fernández-Castanys

En Granada, a 4 de Febrero de 2019

# Contents

# List of Tables

# List of Figures

# Abbreviations

| Abbreviation | Term |
|---|---|
| $\boldsymbol{\eta_G^2}$ | Generalized eta squared |
| $\boldsymbol{1RM}$ | One repetition maximum |
| $\boldsymbol{ANOVA}$ | Analysis of variance |
| $\boldsymbol{BF}$ | Biceps femoris |
| $\boldsymbol{BP}$ | Barometric pressure |
| $\boldsymbol{CMJ}$ | Countermovement jump |
| $\boldsymbol{COM}$ | Center of mass |
| $\boldsymbol{CSA}$ | Cross-sectional Area |
| $\boldsymbol{DAC}$ | Digital-to-analog converter |
| $\boldsymbol{EMG}$ | Electromyography |
| $\boldsymbol{EqFIO_2}$ | Equivalent of the FIO2 at sea level |
| $\boldsymbol{EqPIO_2}$ | Equivalent of the PIO2 at sea level |
| $\boldsymbol{ES}$ | Effect size |
| $\boldsymbol{F_0}$ | Maximal theoretical force |
| $\boldsymbol{F_{100}}$ | Explosive force at 100 ms |
| $\boldsymbol{F_{150}}$ | Explosive force at 150 ms |
| $\boldsymbol{F_{200}}$ | Explosive force at 200 ms |
| $\boldsymbol{F_{50}}$ | Explosive force at 50 ms |
| $\boldsymbol{F_{med}}$ | Median frequency |
| $\boldsymbol{F}$ | F statistic |
| $\boldsymbol{FI_{nsmk}}$ | Fatigue Index |

|  |  |
|---|---|
| $\boldsymbol{FiO_2}$ | Fraction of inspired oxygen |
| $\boldsymbol{GH}$ | Growth hormone |
| $\boldsymbol{GM}$ | Gastrocnemious medialis |
| $\boldsymbol{GRF}$ | Ground reaction force |
| $\boldsymbol{HH}$ | Hypobaric Hypoxia |
| $\boldsymbol{Hz}$ | Hertz |
| $\boldsymbol{IRHT}$ | Intermitent Resistance Hypoxic training |
| $\boldsymbol{kHz}$ | Kilohertz |
| $\boldsymbol{LHTL}$ | Live-high, train-low |
| $\boldsymbol{LLTH}$ | Live-Low, Train-High |
| $\boldsymbol{MU}$ | Motor unit |
| $\boldsymbol{MVIC}$ | Maximal voluntary isometric contraction |
| $\boldsymbol{MVIF}$ | Maximal voluntary isometric force |
| $\boldsymbol{MVIT}$ | Maximal voluntary isometric torque |
| $\boldsymbol{NH}$ | Normobaric Hypoxia |
| $\boldsymbol{P_0}$ | Maximal theoretical power |
| $\boldsymbol{P_{max}}$ | Maximal theoretical power |
| $\boldsymbol{PaO_2}$ | Alveolar partial pressure of oxygen |
| $\boldsymbol{PCO_2}$ | Partial pressure of carbon dioxide |
| $\boldsymbol{PIO_2}$ | Partial pressure of inspired oxygen |
| $\boldsymbol{RF}$ | Rectus femoris |
| $\boldsymbol{RMS}$ | Root mean squared |
| $\boldsymbol{RPE}$ | Rating of perceived exertion |
| $\boldsymbol{SSC}$ | Stretch-Shortening Cycle |
| $\boldsymbol{ST}$ | Semitendinosus |
| $\boldsymbol{V_0}$ | Maximal theoretical velocity |
| $\boldsymbol{VL}$ | Vastus lateralis |
| $\boldsymbol{VM}$ | Vastus medialis |

# Abstract

Intermittent hypoxic resistance training (IHRT) may help to maximize the neural and structural adaptations following resistance training, although conflicting evidence is available. Previous investigations have reported contradicting results as regards the acute and chronic adaptations to hypertrophy-oriented IHRT. However, the potential effects of power-oriented resistance training remain underexplored. Moreover, no previous IHRT investigations have been carried out under conditions of hypobaric hypoxia. Therefore, the main goal of this thesis was to examine the acute and chronic influence of intermittent exposure to moderate hypobaric hypoxia on the functional and neuromuscular responses to power-oriented resistance training. Five separate research experiments were carried out to 1) refine the training and testing tools to assess strength performance and training adaptations (Sections 3.1, 3.2 and 3.3) and 2) investigate the specific influence of intermittent moderate altitude exposure (Sections 3.4 and 3.5).

The first preliminary study (Section 3.1) investigated the effects of a traditional (TT) *vs.* cluster (CT) countermovement jump (CMJ) training on the lower-body force, velocity and power output. Nineteen males were assigned to a CT or a TT group. CT involved three weeks of 6 sets of 3 × 2 repetitions (30s rest every two repetitions and 4min 30s between sets), and TT comprised 6 sets of 6 continuous repetitions (5 min rest between sets), twice a week. At three external loading conditions (25, 50 and 75% of body mass), power ($P_{25}$, $P_{50}$, $P_{75}$), force ($F_{25}$, $F_{50}$, $F_{75}$), and velocity ($V_{25}$, $V_{50}$, $V_{75}$) were obtained during CMJs. The force-velocity (FV) profile was evaluated including the *Slope*, estimated maximal theoretical force ($F_0$), velocity ($V_0$) and power ($P_0$). After CT, moderate increments in $P_{25}$ were observed

compared to TT ($p = 0.011$, ES = 0.55), due to a moderate rise in $V_{25}$ ($p = 0.001$, ES = 0.71) although no significant differences were observed in any of the FV profile variables ($p \geq 0.207$, ES $\leq 0.31$). Accordingly, three weeks of CMJ training including cluster set configurations seem more efficient at inducing velocity and power adaptations, specific to the training load.

A second study (Section 3.2) examined performance and surface electromyography (EMG) changes during a power training protocol comprising continuous or clustered set configurations. Eighteen active males completed six sets of six repetitions during the loaded (20% 1RM) CMJ exercise, continuously (n = 9) or with a 30s pause every two repetitions (cluster; n = 9). Power output and surface EMG from the vastus lateralis (VL), vastus medialis (VM) and rectus femoris (RF) muscles were monitored during all CMJ repetitions. Relative changes from the first repetition were assessed on the EMG root mean square (RMS), median frequency ($F_{\mathrm{med}}$) and a low to high-frequency ratio index of fatigue ($FI_{\mathrm{nsmk}}$). Greater power output decrements were observed during the continuous set configuration ($p = 0.001$, $\eta^2_G <$ 0.01). Greater RMS increments in VL (6.8 ± 11.3 vs. -1.7 ± 5.8%) and RF (9.3 ± 14.2 vs. 1.9 ± 6.9%), but not VM (2.0 ± 4.7 vs. 2.6 ± 7.3%) were also observed in the continuous compared to the cluster sets ($p = 0.033$, $\eta^2_G = 0.06$). Progressive decrements in $F_{\mathrm{med}}$ and increments in $FI_{\mathrm{nsmk}}$ were observed across repetitions in both set configurations, showing unclear effects of cluster sets on EMG parameters, despite of maximizing power output.

A crossectional investigation (Section 3.3) was then carried out to explore relationships between the force-velocity (FV) profile and the isometric muscle torque performance during a unilateral knee-extension task. The FV profile ($F_0$, $V_0$, $P_{max}$, *Slope*) during the CMJ exercise, maximum voluntary isometric torque (MVIT) and explosive voluntary torque production were assessed in 43 participants. Surface EMG was recorded during the isometric assessments and resting muscle architecture measurements were also performed (quadriceps thickness, vastus lateralis pennation angle and fascicle length). Pearson's correlation coefficients were computed to assess bivariate relationships between the FV profile, isometric torque, EMG activation and muscle architecture. $F_0$ predictions from physiological muscle measurements were assessed through multiple linear regression. Associations of $F_0$ and $P_{max}$ with explosive torque increased from early phase to MVIT (r $\geq 0.47$; $p < 0.05$). Significant associations were found between muscle architecture and $F_0$ and $P_{max}$ ($r \geq 0.69$; $p < 0.05$), while $V_0$ and FV *Slope* were unrelated ($r \leq 0.27$; $p > 0.05$). Quadriceps thickness and VL pennation angle explained ~62% of $F_0$ variance. Accordingly, the knee extensors maximal isometric strength and their morphological architecture are strongly related to $F_0$ estimated from a CMJ FV profile test.

The first investigation conducted at moderate altitude (Section 3.4) studied the influence of hypoxia on lower-body strength performance and EMG activation during a power-oriented resistance training session, comprising two different loading conditions. Over four separate experimental trials, twenty-two males completed two squat MVICs followed by six sets of six CMJs repetitions with two different external loading (*heavy*: load associated with a mean propulsive velocity of 1.1 m·s$^{1}$ and *light*: load associated with a mean propulsive velocity of 1.4 m·s$^{1}$), at moderate altitude (2320 m) and normoxic (690 m) conditions. For each repetition, force, velocity and power output were calculated from ground reaction force recordings. Surface EMG signals were also monitored during all repetitions. Changes in EMG amplitude (RMS) and spectral properties ($\mathrm{F}_{\mathrm{med}}$ and $\mathrm{FI}_{\mathrm{nsm5}}$) were assessed. Ratings of perceived exertion (RPE) were also assessed 15 min after each session. Results showed similar MVIF (3434.3 ± 568.3 *vs.* 3440.4 ± 608.2 N, at moderate altitude and normoxia, respectively; $F = 0.02$, $p = 0.900$, $\eta_G^2 < 0.01$), and net CMJ mechanical performance were observed in both altitude levels. Slightly greater RPE values ($F = 5.30$, $p = 0.042$, $\eta_G^2 = 0.05$) and decrements in movement velocity ($F = 7.47$, $p < 0.001$, $\eta_G^2 < 0.01$) during the heavy condition at moderate altitude, and greater mechanical performance impairments during the lighter training session under normoxic conditions. Similar changes in the surface EMG signal (RMS: $F = 0.71$, $p = 0.620$, $\eta_G^2 < 0.01$; $\mathrm{F}_{\mathrm{med}}$: $F = 0.70$, $p = 0.624$, $\eta_G^2 < 0.01$; $\mathrm{FI}_{\mathrm{nsm5}}$: $F = 0.67$, $p = 0.647$, $\eta_G^2 < 0.01$) were observed in both altitude levels.

Eventually, a training intervention study (Section 3.5) was designed to explore the influence of moderate altitude on the functional, neural and muscle architecture responses of the quadriceps muscles following a power-oriented IHRT intervention. Twenty-four active males completed two 4-week consecutive training blocks comprising general strengthening exercises (weeks 1-4) and power-oriented resistance training (weeks 5-8). Training sessions were conducted twice a week at moderate altitude (2320 m; IHRT, n = 13) or normoxia (690 m; NT, n = 11). External load during the second training block was set to the individual load corresponding to a barbell mean propulsive velocity of 1 $\mathrm{m \cdot s}^1$. Pre-post assessments, performed under normoxic conditions, comprised quadriceps muscle architecture (thickness, pennation angle and fascicle length), isometric maximal (MVIF) and explosive strength, and voluntary muscle activation (surface EMG). Dynamic strength performance was assessed through the FV relationship ($F_0$, $V_0$, $P_0$) and a repeated CMJ test ($\mathrm{CMJ}_{15\mathrm{MP}}$). Results showed region-specific muscle thickness changes in both training groups ($p < 0.001$, $\eta^2_G = 0.02$). A small opposite trend in pennation angle changes was observed (ES [90% CI]: -0.33 [-0.65, -0.01] vs. 0.11 [-0.44, 0.6], in the IHRT and NT group, respectively; $p = 0.094$, $\eta^2_G = 0.02$). Both training groups showed similar improvements (i.e. non-significant time × group interaction effects, ANOVA) in MVIF (ES: 0.38 [0.20, 0.56] vs. 0.55 [0.29, 0.80], in the IHRT and NT group, respectively; $p = 0.645$, $\eta^2_G < 0.01$), $F_0$ (ES: 0.41 [-0.03, 0.85] *vs.* 0.52 [0.04, 0.99], in the IHRT and NT group, respectively; $p = 0.569$, $\eta^2_G < 0.01$) and $P_0$ (ES: 0.53 [0.07, 0.98] *vs.* 0.19 [-0.06, 0.44], in the IHRT and NT group, respectively; $p = 0.320$, $\eta^2_G < 0.01$). No meaningful changes in explosive strength performance were observed.

These investigations suggest that, while similar maximal isometric strength and net CMJ mechanical performance during resistance training occur at moderate hypobaric hypoxia, the perceptual and performance fatigability responses may be affected in a load-specific manner. Similar rates of change across efforts are nonetheless observed in the interference EMG signal, highlighting the complex nature of fatigue development and our ability to assess it during dynamic resistance training movements. Moreover, in an active but non-elite population, the short-term adaptive responses to power-oriented resistance training seem to be of similar magnitude at a functional and neuromuscular level in both altitude levels explored.

# Resumen

La exposición intermitente a la altitud moderada (IHRT) podría maximizar las adaptaciones neurales y estructurales al entrenamiento de fuerza, aunque la evidencia es conflictiva. Investigaciones precedentes han mostrado resultados contradictorios en cuanto a los efectos agudos y crónicos del entrenamiento de fuerza orientado a la hipertrofia muscular. Sin embargo, los efectos potenciales del entrenamiento de fuerza orientado a la potencia no han sido estudiados previamente. Además, no existen investigaciones en condiciones de hipoxia hipobárica. Por lo tanto, el objetivo principal de esta tesis fue examinar la influencia aguda y crónica de la exposición intermitente a una altura moderada durante sobre las adaptaciones funcionales y neuromuscular al entrenamiento de potencia. Se llevaron a cabo cinco estudios orientados a 1) desarrollar las herramientas de entrenamiento y evaluación de la fuerza muscular (Secciones 3.1, 3.2 y 3.3) y 2) investigar la influencia de la altura moderada (Secciones 3.4 y 3.5).

El primer estudio preliminar (Sección 3.1) examinó los efectos de un entrenamiento cluster (CT) o tradicional (TT) con el ejercicio de salto con contramovimiento (CMJ) sobrecargado sobre la fuerza, velocidad y potencia de piernas. Diecinueve varones fueron asignados a un grupo CT o TT. Durante 3 semanas (2 sesiones por semana), el entrenamiento CT comprendió 6 series de 3 x 2 repeticiones (descanso: 30s cada dos repeticiones y 4min 30s entre series). El grupo TT realizó 6 series de 6 repeticiones continuas (descanso: 5 min entre series). La fuerza ($F_{25}$, $F_{50}$, $F_{75}$), velocidad ($V_{25}$, $V_{50}$, $V_{75}$) y potencia ($P_{25}$, $P_{50}$, $P_{75}$) fueron examinadas en tres condiciones de sobrecarga externa: 20, 50 y 75% del peso corporal. El perfil de fuerza-velocidad (FV) fue analizado en los parámetros de *Slope*, fuerza máxima teórica ($F_0$),

velocidad ($V_0$) y potencia ($P_0$). Tras el entrenamiento, el grupo CT mostró incrementos moderados en $P_{25}$ ($p = 0.011$, ES = 0.55), en comparación con el grupo TT, principalmente por una mejora de $V_{25}$ ($p = 0.001$, ES = 0.71). No se observaron cambios significativos en las variables derivadas del perfil FV ($p \geq 0.207$, ES $\leq 0.31$). Por lo tanto, tres semanas de entrenamiento de potencia con el ejercicio CMJ comprendiendo una organización de series "cluster" parecen más eficientes en la mejora del rendimiento explosivo ligado a la carga de entrenamiento.

En un segundo estudio, se investigaron cambios en la fuerza y la activación muscular durante una sesión de entrenamiento de potencia con una configuración "cluster" o "tradicional" (Sección 3.2). Dieciocho varones completaron 6 series de 6 repeticiones de CMJ sobrecargado al 20% de 1RM, de forma continua (n = 9) o con una pausa de 30s cada 2 repeticiones (cluster; n = 9). La potencia mecánica y activación muscular del vasto lateral (VL), vasto medial (VM) y recto femoral (RF) fueron monitorizadas durante todas las repeticiones. Se analizaron los cambios relativos desde la primera repetición en medidas de amplitud (RMS) y frecuencia ($F_{med}$, $FI_{nsmk}$) de las señales de EMG. Lo resultados mostraron mayor pérdida de potencia durante las series continuas ($p = 0.001$, $\eta^2_G < 0.01$). Además, se observaron mayores incrementos de RMS en VL (6.8 ± 11.3 vs. -1.7 ± 5.8%) y RF (9.3 ± 14.2 vs. 1.9 ± 6.9%), sin cambios en VM (2.0 ± 4.7 vs. 2.6 ± 7.3%) durante las sesiones continuas en comparación con el método cluster ($p = 0.033$, $\eta^2_G = 0.06$). Ambas configuraciones provocaron una disminución progresiva de la $F_{med}$ y aumento de $FI_{nsmk}$, sin efectos significativos del método cluster.

Se llevó a cabo una investigación cros-seccional para analizar las asociaciones entre los parámetros derivados del perfil FV ($F_0$, $V_0$, $P_{max}$, *Slope*) y medidas de torque isométrico máximo (MVIT) y explosivo en 43 participantes (Sección 3.3). Durante los esfuerzos isométricos se registró la señal de EMG. Además, se llevaron a cabo medidas de arquitectura muscular (grosor, ángulo de penneación y longitud de fascículo) del cuádriceps. Un análisis de correlación de Pearson mostró que la asociación entre la variable $F_0$ y el torque explosivo isométrico aumentó a medida que el torque explosivo se acercaba a MVIT (r $\geq 0.47$; $p < 0.05$). Se encontraron asociaciones significativas entre la arquitectura muscular y las variables $F_0$ y $P_{max}$ (r $\geq 0.69$; $p < 0.05$), sin asociaciones significativas con $V_0$ y *Slope* (r $\leq 0.27$; $p >$

0.05). El grosor muscular y el ángulo de penneación explicaron ~62% de la varianza en $F_0$. Según los resultados, la fuerza máxima isométrica y sus características morfológicas parecen estar estrechamente asociadas con el valor de $F_0$ estimado del perfil FV durante el ejercicio de CMJ.

La primera investigación en condiciones de hipoxia moderada (Sección 3.4) estudió la influencia aguda de la hipoxia sobre el rendimiento de fuerza de piernas y la activación muscular durante una sesión de entrenamiento de potencia. En 4 condiciones experimentales diferentes (2 condiciones de carga y 2 condiciones de altitud), 22 varones completaron un protocolo que comprendió 1) una evaluación de la fuerza máxima isométrica y 2) 6 series de 6 repeticiones continuas durante el ejercicio de CMJ con dos sobrecargas diferentes (*heavy*: sobrecarga asociada a una velocidad media propulsiva de 1.1 $\text{m}\cdot\text{s}^1$ y *light*: sobrecarga asociada a una velocidad propulsiva de 1.4 $\text{m}\cdot\text{s}^1$). Ambos protocolos se llevaron a cabo en condiciones de normoxia (690 m) e hipoxia moderada (2320 m). Para cada repetición de CMJ, variables de fuerza, velocidad y potencia fueron analizadas. La señal de EMG también fue registrada en todas las repeticiones para observar cambios en la amplitud (RMS) y la frecuencia espectral ($\text{F}_{\text{med}}$ y $\text{F}_{\text{nsm5}}$). La percepción subjetiva del esfuerzo (RPE) fue también examinada 15 min después del final de cada sesión experimental. Los resultados mostraron valores similares de MVIF (3434.3 ± 568.3 *vs.* 3440.4 ± 608.2 N, en hipoxia y normoxia; $F = 0.02$, $p = 0.900$, $\eta_G^2 < 0.01$) y rendimiento neto durante las repeticiones de CMJ. Valores ligeramente superiores de RPE fueron observados ($F = 5.30$, $p = 0.042$, $\eta_G^2 = 0.05$) y mayor pérdida de velocidad ($F = 7.47$, $p < 0.001$, $\eta_G^2 < 0.01$) en la condición *heavy* en condiciones de hipoxia, mientras que la pérdida de rendimiento a lo largo de las repeticiones fue mayor en condiciones de normoxia durante la sesión "light". Por el contrario, se observaron cambios similares en ambos grupos experimentales en los parametros analalizados de EMG (RMS: $F = 0.71$, $p = 0.620$, $\eta_G^2 < 0.01$; $\text{F}_{\text{med}}$: $F = 0.70$, $p = 0.624$, $\eta_G^2 < 0.01$; $\text{FI}_{\text{nsm5}}$: $F = 0.67$, $p = 0.647$, $\eta_G^2 < 0.01$).

Por último, se llevó a cabo un estudio de intervención para investigar la influencia de la altitud moderada sobre las adaptaciones funcionales y neuromusculares tras 8 semanas de entrenamiento de potencia (Sección 3.5). 24 sujetos llevaron a cabo el entrenamiento, organizado en 2 bloques de acondicionamiento general (semanas 1-4) y entrenamiento de potencia (semanas 5-8), que comprendió 2 sesiones semanales en condiciones de altitud moderada (2320 m; IHRT, n = 13) o normoxia (690 m; NT, n = 11). Durante el bloque de potencia, la carga de entrenamiento fue aquella asociada a una velocidad media propulsiva de 1 m·s$^1$ durante el ejercicio de CMJ sobrecargado. Los tests pre-post fueron realizados en condiciones de normoxia y comprendieron variables de arquitectura muscular (grosor muscular, angulo de penneación y longitud del fascículo), de fuerza isométrica y activación muscular (EMG de superficie). El rendimiento de fuerza dinámica se analizó a través del perfil FV ($F_0$, $V_0$, $P_0$) y un test de 15 repeticiones continuas de CMJ (CMJ$_{\text{15MP}}$). Los resultados mostraron cambios regionales de grosor muscular en ambos grupos ($p < 0.001$, $\eta^2_G = 0.02$). Una ligera tendencia opuesta en cambios de angulo de penneación fue observada (ES [90% CI]: -0.33 [-0.65, -0.01] *vs.* 0.11 [-0.44, 0.6], en los grupos IHRT y NT, respectivamente; $p = 0.094$, $\eta^2_G = 0.02$). Ambos grupos mostraron mejoras similares (i.e. interacciones tiempo × grupo no significativas) en MVIF (ES, IHRT: 0.38 [0.20, 0.56] *vs.* NT: 0.55 [0.29, 0.80]; $p = 0.645$, $\eta^2_G < 0.01$), $F_0$ (ES, IHRT: 0.41 [-0.03, 0.85] *vs.* NT: 0.52 [0.04, 0.99]; $p = 0.569$, $\eta^2_G < 0.01$), y $P_0$ (ES, IHRT: 0.53 [0.07, 0.98] *vs.* NT: 0.19 [-0.06, 0.44]; $p = 0.320$, $\eta^2_G < 0.01$). No se observaron cambios en la fuerza explosiva isométrica en ninguno de los grupos.

En su conjunto, estas investigaciones sugieren que, aunque la fuerza máxima isométrica y rendimiento neto en CMJ es similar, la percepción del esfuerzo y decremento del rendimiento durante una sesión de potencia pueden estar afectadas por la altura moderada. No obstante, no se observan diferencias en los cambios de las señales de EMG, lo que pone de manifiesto la complejidad de la fatiga muscular y nuestra posibilidad de medirla de forma precisa durante el entrenamiento de fuerza. Además, los resultados de esta tesis doctoral muestran que las adaptaciones funcionales y neuromusculares tras 16 sesiones de entrenamiento de fuerza orientadas a la mejora de la potencia no están influenciadas por la altura moderada, al menos en la población de estudio empleada.

# Scientific contributions

### Publications arising from this doctoral thesis

*Scientific articles:*

- **Morales-Artacho, A. J.**, Padial, P., García-Ramos, A., Pérez-Castilla, A., & Feriche, B. (2018). Influence of a Cluster Set Configuration on the Adaptations to Short-Term Power Training. *Journal of Strength and Conditioning Research*, 32(4), 930–937. doi: 10.1519/JSC.0000000000002811
- **Morales Artacho, A. J.**, García-Ramos, A., Pérez Castilla, A., Padial, P., Gomez, A., Peinado, A. M., Pérez-Córdoba, J.L.,Feriche, B. (2018). Muscle activation during power-oriented resistance training: Continuous vs. cluster set configurations. *Journal of Strength and Conditioning Research*, Sep 17. doi: 10.1519/JSC.0000000000002811 [Epub ahead of print]
- **Morales-Artacho, A. J.**, Ramos, A. G., Pérez-Castilla, A., Padial, P., Argüelles-Cienfuegos, J., de la Fuente, B., & Feriche, B. (2018). Associations of the Force-Velocity Profile with Isometric Strength and Neuromuscular Factors. *International Journal of Sports Medicine*, 2018 Oct 5. doi: 10.1055/a-0644-3742 [Epub ahead of print]
- **Morales-Artacho, A. J.**, Padial, P., García-Ramos, A., Pérez-Castilla, A., Argüelles-Cienfuegos, J., De la Fuente, B., & Feriche, B. (2018). Intermittent resistance training at moderate altitude: Effects on the force-velocity relationship, isometric strength and muscle architecture. *Frontiers in Physiology*, 9: 594. doi: 10.3389/fphys.2018.00594

*Conference proceedings:*

- **Morales-Artacho, A. J.**, García-Ramos, A., Pérez-Castilla, A., Padial, P, Argüelles, J.; de la Fuente, B.; Feriche, B.,. Assessing muscle strength: how does the force-velocity profile related to maximal and explosive isometric strength performance on the knee extensors? Book of Abstracts, X International Symposium in Strength Training: Facultad de Ciencias del Deporte. Universidad Politécnica de Madrid, 2017.

### Other contributions

*Scientific articles:*

- Acosta, F. M., Martinez-Tellez, B., Sanchez-Delgado, G., A Alcantara, J. M., Acosta-Manzano, P., **Morales-Artacho, A. J.**, & R Ruiz, J. (2018). Physiological responses to acute cold exposure in young lean men. PloS One, 13(5), e0196543. https://doi.org/10.1371/journal.pone.0196543

- Balshaw, T. G., Massey, G. J., Maden-Wilkinson, T. M., **Morales-Artacho, A. J.**, McKeown, A., Appleby, C. L., & Folland, J. P. (2017). Changes in agonist neural drive, hypertrophy and pre-training strength all contribute to the individual strength gains after resistance training. European Journal of Applied Physiology, 117(4), 631–640. https://doi.org/10.1007/s00421-017-3560-x

- 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. https://doi.org/10.1519/JSC.0000000000000821

- Castillo, F., Valverde, T., **Morales-Artacho, A. J.**, Pérez-Guerra, A., de León, F., & García-Manso, J. M. (2012). Maximum power, optimal load and optimal power spectrum for power training in upper-body (bench press): a review. Revista Andaluza de Medicina Del Deporte, 5(1), 18–27. https://doi.org/10.1016/S1888-7546(12)70005-9

- Feriche, B., García-Ramos, A., **Morales-Artacho, A. J.**, & Padial, P. (2017). Resis-

tance Training Using Different Hypoxic Training Strategies: a Basis for Hypertrophy and Muscle Power Development. Sports Medicine - Open, 3. https://doi.org/10.1186/s40798-017-0078-z

- García-Ramos, A., Torrejón, A., Feriche, B., **Morales-Artacho, A. J.**, Pérez-Castilla, A., Padial, P., & Haff, G. G. (2017a). Prediction of the Maximum Number of Repetitions and Repetitions in Reserve From Barbell Velocity. International Journal of Sports Physiology and Performance, 1–23. https://doi.org/10.1123/ijspp.2017-0302
- García-Ramos, A., Torrejón, A., Feriche, B., **Morales-Artacho, A. J.**, Pérez-Castilla, A., Padial, P., & Jaric, S. (2017b). Selective effects of different fatigue protocols on the function of upper body muscles assessed through the force–velocity relationship. European Journal of Applied Physiology, 1–9.
- García-Ramos, A., Torrejón, A., **Morales-Artacho, A. J.**, Pérez-Castilla, A., & Jaric, S. (2018). Optimal Resistive Forces for Maximizing the Reliability of Leg Muscles' Capacities Tested on a Cycle Ergometer. Journal of Applied Biomechanics, 34(1), 47–52. https://doi.org/10.1123/jab.2017-0056
- García-Ramos, A., Torrejón, A., Pérez-Castilla, A., **Morales-Artacho, A. J.**, & Jaric, S. (2017). Selective Changes on the Mechanical Capacities of Lower Body Muscles After a Cycle Ergometer Sprint Training Against Heavy and Light Resistances. International Journal of Sports Physiology and Performance, 1–22. https://doi.org/10.1123/ijspp.2017-0239
- **Morales-Artacho, A. J.**, Lacourpaille, L., & Guilhem, G. (2017). Effects of warm-up on hamstring muscles stiffness: Cycling vs foam rolling. Scandinavian Journal of Medicine & Science in Sports, 27(12), 1959–1969. https://doi.org/10.1111/sms.12832
- **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(1), 149–156. https://doi.org/10.1515/hukin-2015-0043

- **Morales-Artacho, A. J.**, Padial, P., Rodríguez-Matoso, D., Rodríguez-Ruiz, D., García-Ramos, A., García-Manso, J. M., … Feriche, B. (2015). Assessment of Muscle Contractile Properties at Acute Moderate Altitude Through Tensiomyography. High Altitude Medicine & Biology, 16(4), 343–349. https://doi.org/10.1089/ham.2015.0078

- Pérez-Castilla, A., García-Ramos, A., Padial, P., **Morales-Artacho, A. J.**, & Feriche, B. (2017). Load-velocity relationship in variations of the half-squat exercise: Influence of execution technique. Journal of Strength and Conditioning Research. https://doi.org/10.1519/JSC.0000000000002072

- Pérez-Castilla, A., García-Ramos, A., Padial, P., **Morales-Artacho, A. J.**, & Feriche, B. (2018). Effect of different velocity loss thresholds during a power-oriented resistance training program on the mechanical capacities of lower-body muscles. Journal of Sports Sciences, 36(12), 1331–1339.

*Conference proceedings:*

- Almeida, F; Bonitch-Góngora, J; Padial, P.; **Morales-Artacho,A. J.**; Shoenfeld, B.J.; de la Fuente, B.; Calderón, C.; Feriche, B. Effect of a power-oriented resistance Training program at moderate altitude on the force-velocity relationship in elite judokas. Journal of Strength and Conditional Research, 2018:32(9), e15-e16.

- Stirn,I.; Tomazin,K., M Smajla, D.; Strojnik, V.; Padial, P.; Almeida, F.; **Morales-Artacho, A. J.**, et al.; Effect of altitude strength training on neuromuscular function. Book of Abstracts, 23rd Annual Congress of the European College of Sport Science, 2018: 978-3-9818414-1-1

- Feriche, B., **Morales-Artacho, A. J.**, García-Ramos, A., Pérez-Castilla, A., Padial, P. Intermittent hypoxic resistance training affects the force-velocity profile. Book of Abstracts, 22nd Annual Congress of the European College of Sport Science. Cologne, Germany: European College of Sport Science, 2017.

- Guilhem, G., **Morales Artacho, A. J.**, & Lacourpaille, L. Effects of warm-up on hamstring muscles stiffness: cycling vs. foam rolling. Cologne, Germany: European College of Sport Science, 2017.

- **Morales Artacho, A. J.**, Padial, P., Calderón, C., Rodríguez-Matoso, D., García-Manso, J. M., & Feriche, B. Effect of acute exposure to moderate altitude on the muscle contractile properties measured by tensiomyography. Book of Abstracts, IV NSCA International Conference. Murcia, Spain, 2014.

# Research grants

The present doctoral thesis has been possible thanks to the following research funding:

- PhD fellowship (Formación del Profesorado Universitario; FPU13/04801) from the Spanish Ministry of Education.
- Research Grant "Influencia de la estrategia de exposición a la hipoxia moderada sobre las adaptaciones al entrenamiento de la potencia muscular" funded by the Spanish Ministry of Economy and Competitiveness (2016-2018, Ref: DEP2015-64350-P; Principal Investigator: M. Belén Feriche Fernández-Castanys; 71148 Euros).

# Research stays

**Stay 1**: A four-month research stay (from the 28th of September 2015 to the 31st of January 2016) was carried out at the French Institute of Sport (INSEP, Paris), which allowed training and experience on the ultrasound-based assessment of muscle mechanical properties.

**Stay 2**: A one-month stay (May-June, 2017) was performed at the Sierra Nevada Sport Performance Center. It involved constant training monitoring and performance assessment of an elite judo team carrying out an altitude training camp (Funding: Research Grant DEP2015-64350-P).

**Stay 3**: A six-month research stay (from the March to August 2017) was performed at the French Institute of Sport (INSEP, Paris) to get a deeper understanding of the biomechanical assessment of muscle-tendon mechanical properties and their responses to mechanical loading.

# Chapter 1

# Introduction

Altitude training remains common practice among elite athletes aiming to improve sea-level sports performance. Since the 1968 Mexico Olympic Games, held at an altitude of 2240m and where decrements in endurance performance and unexpected Olympic records in explosive-related disciplines occurred (Figure 1.1), the interest of physical training under altitude conditions continues growing. The direct influence of environmental hypoxia on the human oxygen carrying capacity has traditionally linked altitude training with endurance-related sports. On the contrary, despite the relevance of the neuromuscular function for not only strength-related but also endurance sports, little attention has been usually paid to the potential positive influence of performing strength training at higher altitudes.

Previous experiments conducted during expeditions and simulations to the highest points on Earth revealed that, unlike endurance performance (Grocott et al. 2009), the neuromuscular ability to generate maximal force levels is preserved (Rupp and Perrey 2009). On the contrary, prolonged exposures to very high and extreme altitudes, without carefully controlling nutrition and sleeping habits, have been often associated with muscle atrophy and impaired performance. Moreover, experimental evidence has shown greater neuromuscular fatigue development at altitude, which could potentially suggest suboptimal conditions to maximize neuromuscular adaptations associated with power training. Notwithstanding, while the experimental evidence available from high altitude expeditions is of great relevance,

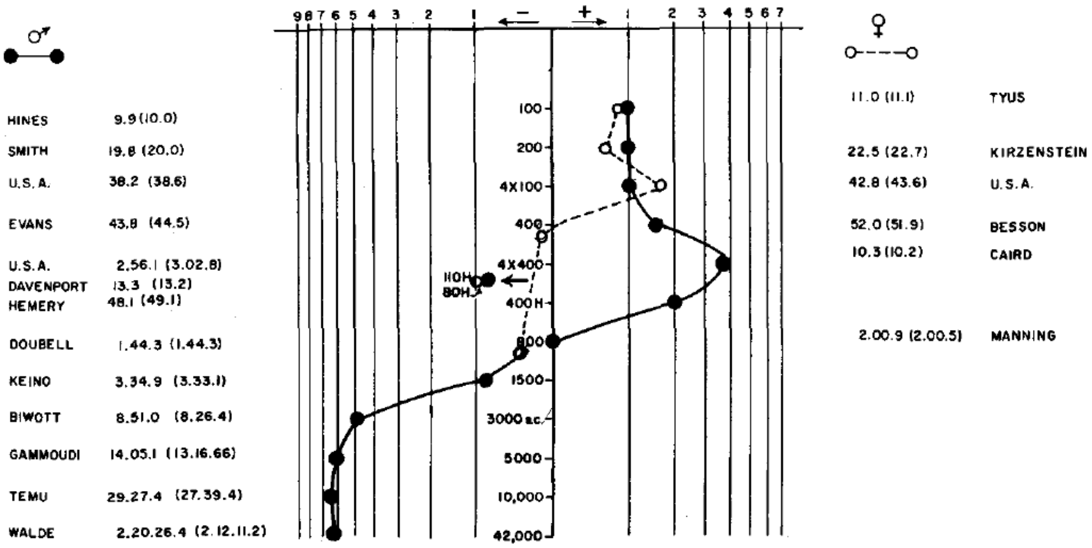

**Figure 1.1:** Percentage deviation of Mexico City winning times from World records in males and females. From Jokl et al. (1969).

the potential influence of environmental hypoxia on the strength training acute and chronic responses remains largely unexplored.

Early hypotheses, presenting altitude as a harmful environment for skeletal muscle development (Ferretti, Hauser, and di Prampero 1990; Narici and Kayser 1995), have been progressively challenged by the idea of using hypoxia to maximize muscle strength responses (Deldicque and Francaux 2013; Feriche et al. 2017). It has been suggested that combining systemic hypoxia during training, and normoxia during recovery (i.e. intermittent hypoxic resistance training [IHRT]), could confer an advantageous stimulus to maximize the muscle adaptations following resistance training (Scott, Slattery, and Dascombe 2014). Nonetheless, despite the increasing research activity, the evidence remains conflictive and limited to simulated altitude studies comprising hypertrophy-oriented resistance training programs. The potential influence of terrestrial moderate altitude on dynamic explosive performance (Feriche et al. 2014; Hamlin, Hopkins, and Hollings 2015) and the specific adaptive responses to power-oriented resistance training encourage further research. This thesis comprises a series of separate research experiments aiming to 1) refine the training and testing methodology commonly used during power-oriented resistance training and 2) to explore the acute and chronic consequences of training at moderate altitude conditions.

The following subsections will introduce the main theoretical background supporting the experimental work conducted in the present doctoral work. Important factors around the power-training practices are highlighted in Section 1.1. Relevant tools and procedures used to assess muscle strength and to monitor resistance training are then introduced in Section 1.2. Eventually, the topic of altitude training with special emphasis on the neuromuscular responses and their implications for power-oriented hypoxic resistance training are addressed in Section 1.4.

## 1.1 Power-oriented resistance training

Common athletic tasks in sport are highly determined by the ability to produce high rates of force and power development. Indeed, the limited time available to apply force in many athletic movements has traditionally encouraged to better understand what determines fast muscle production (Aagaard et al. 2002b) and how it may be enhanced through power-oriented training interventions (Haff and Nimphius 2012). Throughout this manuscript, the concepts of "power" or "explosive" training will be used to generally refer to the well-extended training practices purposely designed to maximize the human ability to develop impulse during a given task (Winter et al. 2016).

Sets, repetitions, rest periods, exercises and loading conditions during resistance training can be optimally orchestrated to target specific adaptations (Haff and Nimphius 2012). In this context, previous research efforts have allowed to better understand how the short- and long-term adaptive responses to power-oriented resistance training may be influenced by factors such as the type of contraction, external loading conditions or movement patterns. Moreover, given the highly specific training responses of the neuromuscular system (Aagaard et al. 2002b; Folland, Buckthorpe, and Hannah 2014), increasing research provides also empirical evidence for the key role of instruction task (Sahaly et al. 2001) or strength level (James et al. 2018). Regardless of the type of contraction, maximal intention to move fast and limited neuromuscular fatigue during explosive training are key factors to maximize adaptation. Accordingly, few repetitions per set (i.e. $< 6$), complete resting periods between sets (i.e. $> 3$ min) and instructions to move as fast as possible are common power-training guidelines (Haff and Nimphius 2012). The following sub-sections provide a general overview of the factors proposed in the literature affecting the acute and adaptive responses to power-oriented resistance training (Cormie, McGuigan, and Newton 2011a).

### 1.1.1 Strength level

Considering the direct relationship between muscular force and power production, it is not surprising that stronger individuals display also a greater capacity for power production in a given standardized movement (Baker and Newton 2008). While untrained individuals may benefit from general resistance training practices, the specificity and relevance of power training methods increase with an individual's strength level. Although the empirical evidence remains limited, increasing research suggests that stronger individuals are more responsive to power-oriented resistance training (Cormie, Mcguigan, and Newton 2010; James et al. 2018). The morphological (i.e. greater CSA, optimized muscle-tendon unit [MTU] mechanical properties) and neuromuscular (i.e. greater neural drive, improved muscle coordination) properties associated to long term resistance training likely have a positive impact on the high neural activation levels required to improve maximal power output (Cormie, McGuigan, and Newton 2011b). These ideas back-up most of the traditional resistance training periodization paradigms comprising the progressive enhancement of technique and maximal strength before targeting explosive adaptations (Haff and Nimphius 2012).

While the influence of strength levels on the adaptations to ballistic training conforms a research question itself, it is also relevant for other research questions concerning the optimization of power training (e.g. altitude training strategies). Building a strength foundation prior to exploring the effects of a given ballistic exercise, protocol or environmental condition may increase the significance of the results, particularly in non-elite sport populations.

### 1.1.2 Contraction mode

Compared to traditional resistance movements, ballistic actions such as jumping or throwing maximize acceleration throughout the whole range of motion. During the bench-press exercise, greater force, velocity and power output levels have been described across different loading external conditions when the barbell is thrown (Newton et al. 1996; Cronin, McNair, and Marshall 2001; García-Ramos, Jaric, Padial, et al. 2016). Greater mechanical performance has also been observed during ballistic (i.e. squat jump or CMJ) compared to squat training exercises (Pérez-Castilla, García-Ramos, et al. 2017). Further evidence at the muscle activation (Cronin, McNair, and Marshall 2001) and motor unit (MU) behaviour level (Zehr and Sale 1994) has also been reflected in the scientific literature. Not only the longer accelerating phase, but also the ballistic nature of the movement may have implications for motor unit recruitment (Zehr and Sale 1994) and adaptation following training (Newton, Kraemer, and Häkkinen 1999). Accordingly, the use of ballistic tasks during resistance training interventions aiming to maximize the ability to generate high levels of power seems warranted.

### 1.1.3 Loading conditions

The role of external loading conditions (i.e. body and external mass to be accelerated) during power training have received particular attention in the literature. Performance fatigability (Izquierdo et al. 2006; Sánchez-Medina and González-Badillo 2011; García-Ramos et al. 2015) and long term adaptations may be significantly influenced by the loading conditions. Indeed, during a given exercise, mechanical performance (i.e. force, velocity and power) is directly influenced by the loading conditions. The external load at which maximal power output is achieved has been often used as a methodological rationale to maximize training adaptation (Cormie et al. 2007). Notwithstanding, considering the variable biomechanical conditions in athletic situations, improving the ability to apply force at different movement velocities has been considered in comprehensive power training interventions (Haff and Nimphius 2012; Cormie, McGuigan, and Newton 2011a). Despite the scarce mechanistic research, recent studies are evidencing the different mechanical stimulus at the muscle-tendon unit level with different loading conditions (Earp et al. 2016; Earp et al. 2017), which may mediate specific muscle morphological changes (Coratella et al. 2018).

### 1.1.4 Resting periods

Under isoinertial conditions, reductions in force, velocity and mechanical power output occur when continuous repetitions are performed at maximal intended velocity (Izquierdo et al. 2006). For example, during bench press and squat exercises, unintentional decrements in movement velocity have been shown to occur as neuromuscular fatigue develops (Sánchez-Medina and González-Badillo 2011). It is thus commonly proposed that fatigue should be minimized, and training intensity maximized (i.e. movement velocity) when training for maximal neuromuscular adaptations (Haff and Nimphius 2012).

Appropriate manipulation of the training sets configuration (i.e. implementing resting periods between repetitions or groups of repetitions) seems to be useful at enhancing mechanical variables and potentially improving power training adaptations (Haff et al. 2008). Compared to traditional set configurations, the squat-jump (Hansen, Cronin, and Newton 2011), ballistic bench-press (García-Ramos et al. 2015) and clean exercises (Hardee et al. 2012) have been shown to benefit from cluster loading configurations (i.e. higher power output and movement velocity). However, while the mechanisms behind the benefits of cluster training are likely related to limited neuromuscular fatigue development, the evidence is scarce (Río-Rodríguez, Iglesias-Soler, and Fernández del Olmo 2016) and no other studies have provided evidence for the influence of resting periods between repetitions on the myoelectric fatigue manifestations. Indeed, despite the practical relevance, our ability to non-invasively explore neuromuscular fatigue development during resistance training remains conflictive and methodologically challenging (Enoka and Duchateau 2016).

On this basis, it is suggested that ballistic explosive training comprising cluster sets may lead to greater performance adaptations than training periods involving traditional set configurations (Haff et al. 2008). However, despite the widespread acute benefits, very few studies have attempted to evaluate the chronic effects of cluster loadings on adaptation. Lawton et al. (2004) did not find superior power output improvements using a cluster set configuration (8 sets × 3 reps every 113 s) after 6 weeks of bench press training. On the contrary, following an eight-week resistance training intervention on elite rugby players, Hansen et al. (2011) described positive effects of cluster loading (resting periods between clusters ranged from 10 to 30s) on peak power and velocity during the squat-jump exercise. Having greater resting time between repetitions not only may reduce the accumulation of metabolic products associated with fatigue development, but also may allow to maximize the voluntary intention to move as fast as possible. Considering that fatigue may not be a necessary stimulus to trigger neuromuscular adaptations (Folland et al. 2002), clustering repetitions within sets seems a reasonable methodological approach to maximize neuromuscular adaptation.

## 1.2 Assessing strength performance

Assessing muscle strength remains an important and common process in sport and human performance testing (McMaster et al. 2014). Muscle strength assessment procedures may comprise dynamic (e.g. isoinertial, isokinetic) or static (i.e. isometric) conditions and are usually selected by practitioners according to exercise training goals, sport specific demands (Giroux et al. 2016) or individual athlete needs (Jiménez-Reyes et al. 2017). While maximal strength in athletic performance is of paramount importance (Suchomel, Nimphius, and Stone 2016), the ability to apply force at high velocities and the rate of torque development (RTD) are considered fundamental in many specific situations where force must be applied in short periods of time (Tillin, Pain, and Folland 2013a; Aagaard et al. 2002b). Accordingly, both dynamic and isometric muscle strength testing procedures usually imply assessing not only maximal strength levels but also the ability to produce force quickly (Folland, Buckthorpe, and Hannah 2014; Samozino et al. 2012; Aagaard et al. 2002b).

### 1.2.1 Maximal strength

The maximum weight an individual can lift once during a given movement is known as one repetition maximum (1RM) and has been traditionally used as a valid and useful assessment of maximal strength during a particular movement (McMaster et al. 2014). Maximal dynamic strength assessments have been long used not only to evaluate training adaptations but also to help in training load prescription. Different factors such as warm-up, exercise technique (e.g. squat depth) or materials should be carefully considered to maximize the validity and reproducibility of 1RM testing (McMaster et al. 2014). Standardization of the warm-up procedure is important not only to optimize performance, but to minimize risk of injury. Following a short period (5-10 min) of continuous activity, along with joint mobility and activation tasks, progressively loaded attempts are usually performed to reach the 1RM load. Although the incremental loading steps depend on the training experience and strength levels, live feedback from a linear position or velocity transducer device may help to optimize the number of attempts and estimate maximal strength (Bazuelo-Ruiz et al. 2015). When assessed during the squat exercise, 1RM values are highly dependent on the squat depth, which must be accurately controlled and reported when it comes to comparing results across studies. Squat depth is frequently controlled during SJ and CMJ using procedures such as using an adjustable rod on a tripod (Bazuelo-Ruiz et al. 2015), elastic bands or telemetric photocells (Pérez-Castilla, García-Ramos, et al. 2017). Alternatively, the displacement of the barbell recorded with a linear position transducer can also be a valid alternative to provide feedback and control of the squat depth. When assessed under isometric conditions, maximum strength is tipically assessed during a maximal voluntary isometric contraction (MVIC) and defined as the maximal voluntary isometric force (MVIF) or torque (MVIT). Figure 1.2 shows a tipical signal force-time example of maximal voluntary isometric contraction performed during the squat position.

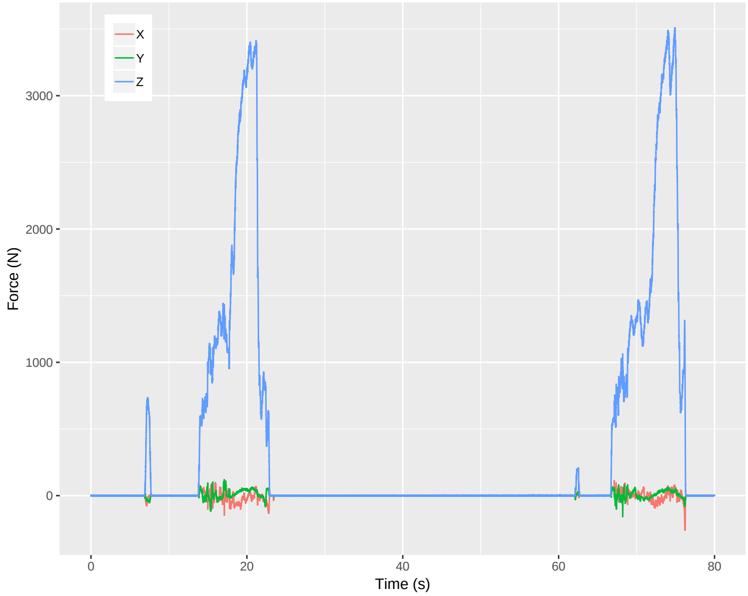

**Figure 1.2:** Ground reaction force recording using a force plate during two attempts of maximal voluntary isometric force (MVIF) during the squat position.

### 1.2.2 Fast force development

Considering the relevance of fast force production in many athletic tasks, increasing attention is being paid to the assessment of explosive performance. Given the similarities between ballistic movements (i.e. jumping, throwing) and real life athletic situations, jumping performance during controlled experimental conditions has been widely employed to evaluate explosive strength performance (Bosco, Luhtanen, and Komi 1983). The CMJ exercise, comprising first an active eccentric stretch rapidly followed by a propulsive concentric phase, provides an interesting set-up to evaluate explosive performance (Komi and Nicol 2010). Measurements of ground reaction force (GRF) using a force plate (Linthorne 2001), or barbell displacement and velocity from a linear position transducer device (Pérez-Castilla, Feriche, et al. 2017) during a CMJ repetition can provide useful performance outcomes (Figure @ref@(fig:figcmj); signal proccesing details are provided in Section 6.1).

Although measurements of RFD may be obtained during a given CMJ movement (Haff et al. 1997), isometric conditions have been suggested to provide a more stable mechanical situation (i.e. constant MTU length) that may increase its validity and reproducibility (Tillin, Pain, and Folland 2012). Considering the high variability commonly reported in RFD measure-

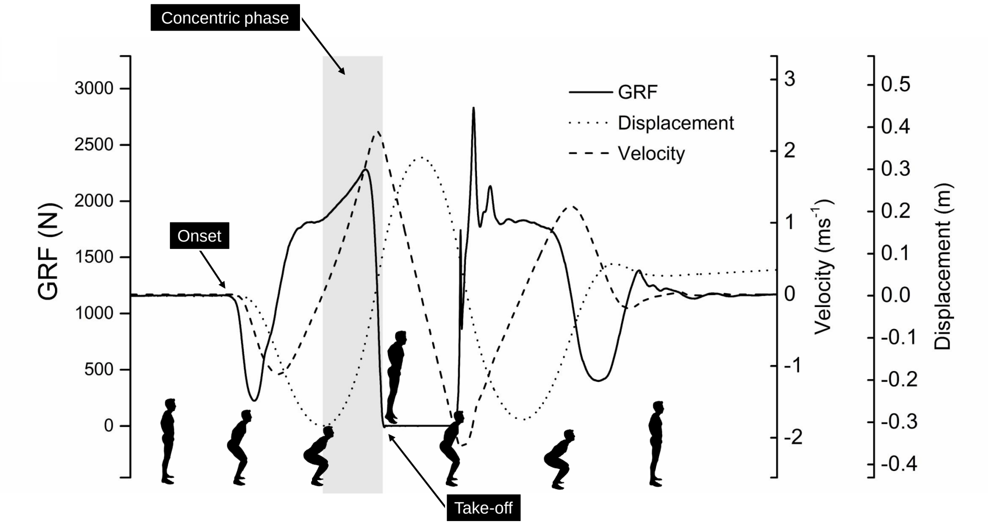

**Figure 1.3:** Ground reaction force, velocity and displacement of the COM during a countermovement jump repetition. The grey-shaded area indicates the concentric phase defined as the perdiod between velocity = 0 and the take-off instant (i.e. GRF < 5 N).

ments, notably at early phases of the contraction, several methodological considerations have been proposed to ensure the validity and reproducibility of the measurement (Maffiuletti et al. 2016). For example, specific intructions (“*Contract as fast and as hard as possible*”) have been shown to maximize isometric RFD (Sahaly et al. 2001). The compliance of the measurement device is also a potential source of error and hard-padded devices are recomended to ensure minimal deformation during contraction (Maffiuletti et al. 2016). Other methodological considerations involve the signal proccesing and contraction onset determination procedures, which may be of particular relevance for strength measures at very early phases of the contraction. Accordingly, pre-tension or co-contraction prior to the contraction onset are potential counfunding factors and should be carefully avoided (Maffiuletti et al. 2016). A graphical example of explosive contractions recordings is provided in Figure 1.4).

### 1.2.3 Force-velocity relationship

The force-velocity (FV) relationship has been traditionally employed to comprehensively assess dynamic strength performance during common athletic tasks (e.g. jumping) (Jaric 2015;

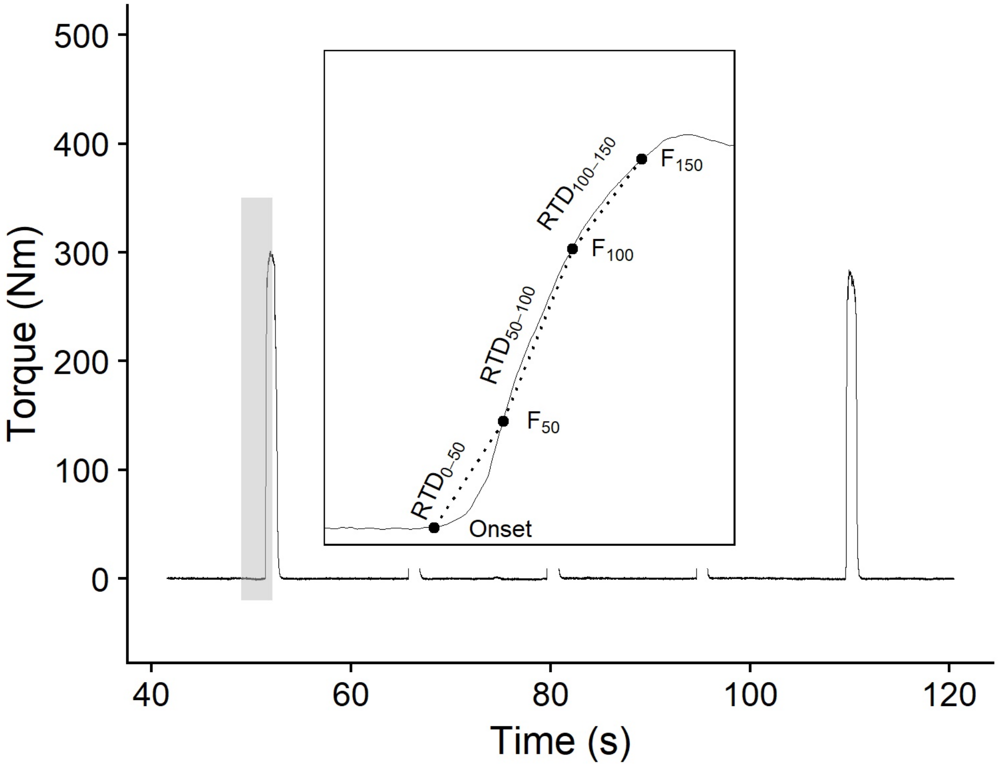

**Figure 1.4:** Typical example of torque trace during an isometric explosive strength assessment.

Morin and Samozino 2016). While single-loading dynamic strength measures (i.e. 1RM, body weight vertical jumping) can inform about strength performance (Thomas et al. 2015; Secomb et al. 2016; Khamoui et al. 2011), specific information regarding the neuromuscular system ability to produce maximal force ($F_0$, force-intercept), velocity ( $V_0$, velocity-intercept) and power ($P_{max}$; $F_0 \times V_0/4$ (Vandewalle et al. 1987)) may be estimated by linearly modelling the relationship between force and velocity outcomes obtained during a progressively loaded test. These relationship may have potential practical applications in both, strength assessment and training intensity prescription.

Preceded by a standardized warm-up protocol, an incremental CMJ test at several progressive loading conditions is usually performed. Force and velocity computation (as detailed in Section 6.1) at each loading condition allows linear modeling and evaluation of specific performance at each loading condition. The use of a Smith Machine increases measurement validity (when assessed using a linear position transducer) and ensures that maximal jumping intention can be safely performed, although both constrained and uncontrained procedures

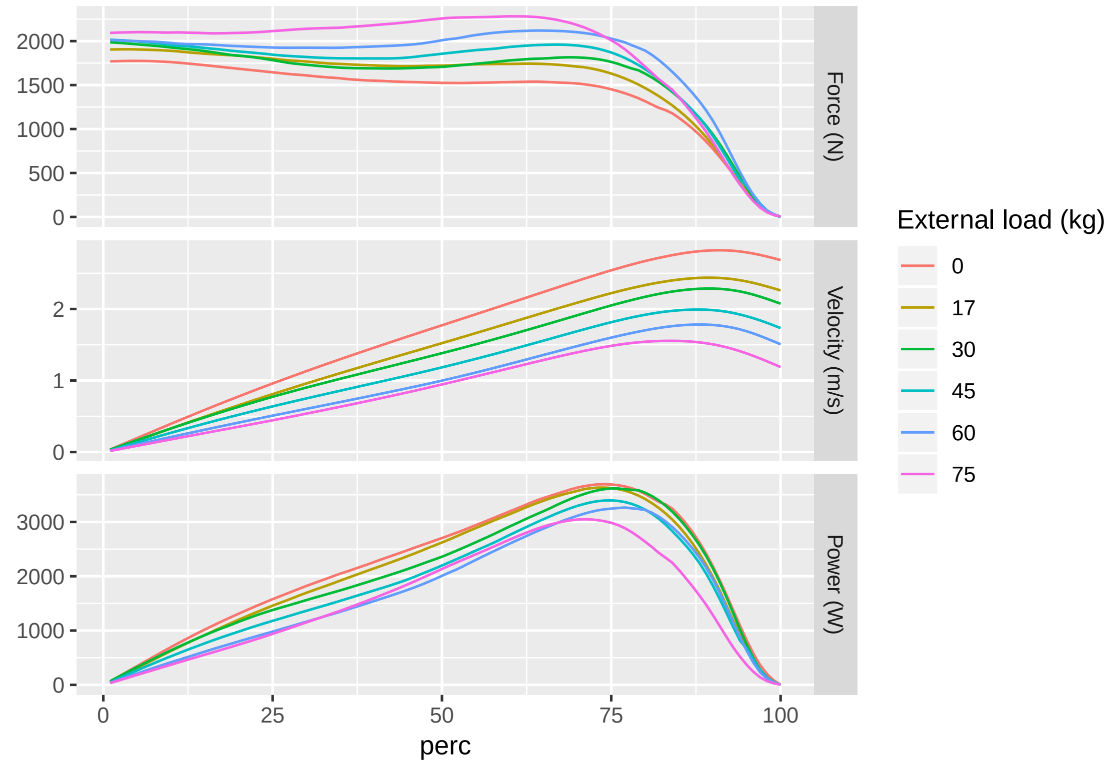

**Figure 1.5:** Example of force, velocity and power time-normalized curves obtained during counter-movement jump exercises at different external loading conditions. Linearly modeling the relationship between peak or mean force and velocity values at each load, allows calculation of the force-velocity profile related variables.

have been proved highly reliable (García-Ramos, Jaric, Pérez-Castilla, et al. 2017).

However, while meaningful maximal isometric force estimations may be achieved from the FV relationship (Sugiura et al. 2016), scarce information is available regarding the potential associations between the FV profile parameters and explosive strength performance assessed in isometric conditions. One study previously evaluated the association between the FV profile measured on a cycle ergometer and knee extension isometric strength performance (Driss et al. 2002). The authors reported meaningful associations of $F_0$ and $P_{max}$ with isometric rate of force development and maximal voluntary force, although the underlying mechanisms remain unexplored.

Neural and structural factors are known to strongly determine the muscle maximal and explosive strength capabilities (Folland and Williams 2007). Previous investigations have documented the influence of muscle size (Trezise, Collier, and Blazevich 2016), architectural

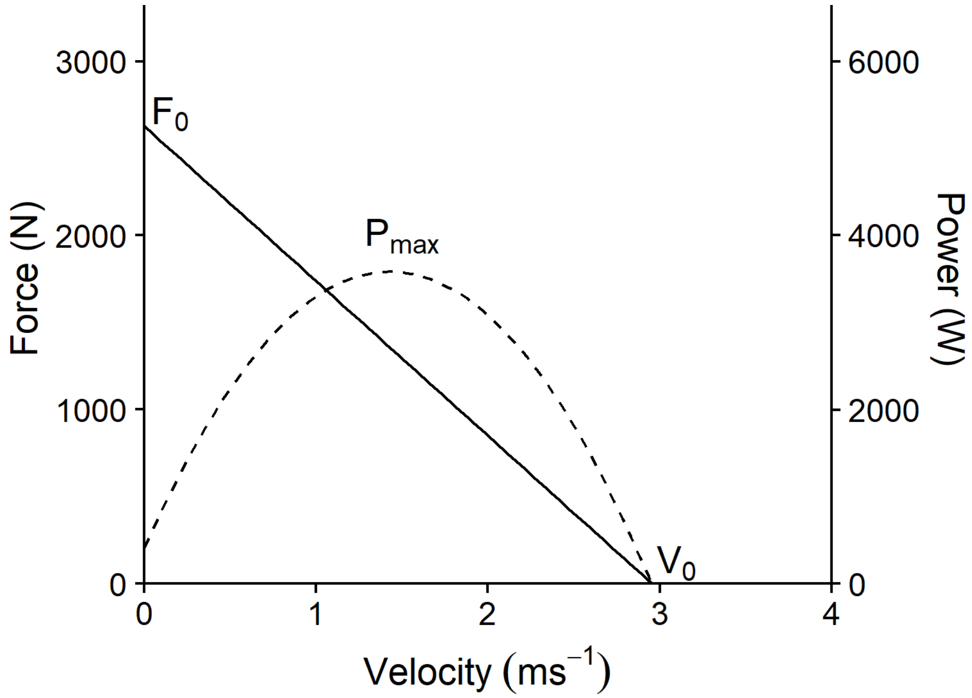

**Figure 1.6:** Typical force-velocity profile (theoretical values) showing the theoretical maximal force ($F_0$), velocity, ($V_0$) and power ($P_{max}$) values.

properties (i.e. pennation angle, fascicle length) (Aagaard et al. 2001) and muscle activation (Andersen and Aagaard 2006) on strength performance, usually measured under single-joint isometric or isokinetic conditions. While muscle size and pennation angle significantly influence maximal strength (Blazevich et al. 2009), greater fascicle lengths and smaller pennation angles are thought to positively affect skeletal muscle shortening velocity (Lieber and Fridén 2000). Additionally, rapid muscle activation is key for explosive muscle force production (Folland, Buckthorpe, and Hannah 2014), although there is conflictive evidence regarding its role on jumping performance (de Ruiter et al. 2006; de Ruiter et al. 2007). Despite the in vitro (Wickiewicz et al. 1984; Lieber and Fridén 2000) and in vivo experimental evidence (Secomb et al. 2016; Trezise, Collier, and Blazevich 2016) showing the importance of muscle arquitecture and muscle activation for explosive force production, little is known about how these mechanisms relate with the information obtained from the FV relationship. Given the practical relevance of the FV profile to estimate the maximal force (i.e. $F_0$) or velocity ($V_0$) muscle mechanical capabilities in the field, further reserarch seems warranted.

### 1.2.4 Monitoring power-oriented resistance training

Objective monitoring of effort intensity and volume during resistance training remains a key question concerning research and practice (Scott et al. 2016). Intensity has been traditionally prescribed relative to maximal strength levels (i.e. 1RM), although other approaches comprising maximal repetitions or repetitions in reserve are also being increasingly used (García-Ramos, Torrejón, et al. 2017). When repetitions are performed at maximal intended velocity, as it is the case for power training, there exist a close relationship between movement velocity and relative intensity. Accordingly, monitoring movement velocity during resistance training may be a useful approach to estimate maximal (Bazuelo-Ruiz et al. 2015) and relative strength levels (González-Badillo and Sánchez-Medina 2010), to assess fatigue development (Izquierdo et al. 2009; Sánchez-Medina and González-Badillo 2011) and to help in training volume prescription (González-Badillo et al. 2017; Pérez-Castilla et al. 2018). In this context, technological advances are helping to easily monitor and provide feedback of movement velocity (i.e. linear position transducers or accelerometry-based devices). Their use during resistance training provide multiple opportunities to maximize the short- and long term adaptations (Randell et al. 2011). Notwithstanding, despite the potential use of measuring movement velocity to inform about external load, the experimental evidence remains limited, and other methodological elements should be considered to reach a more comprehensive approach of resistance training monitoring (Scott et al. 2016). For instance, the resting periods between or within sets of repetitions are also considered key element directly influencing workload density and hence the training stimulus (Bird, Tarpenning, and Marino 2005).

Considering the technical and methodological challenges to accurately control resistance training from external load (Scott et al. 2016), systematic assessment of subjective perceived exertion ratings may be a useful approach to have a more precise control of the resistance training proccess (Sweet et al. 2004). Providing a global rating of the difficulty of a given training session (i.e. session RPE), ~15min after its completion (Kraft, Green, and Thompson 2014), has been shown to be a reliable and valid indicator resistance training intensity (Day et al. 2004; McGuigan, Egan, and Foster 2004).

### 1.2.5 Performance fatigability during power-oriented resistance training

Surface electromyography (EMG) has been widely used to study myoelectric symptoms of exercise-induced muscle fatigue. Despite its inherent limitations (Farina, Negro, and Dideriksen 2014; Del Vecchio et al. 2017), notably during dynamic muscle efforts (Farina 2006), different changes in the EMG signal time and frequency domains have been previously linked to muscle fatigue development. Specifically, a left shift in the frequency spectrum and an increase in the EMG signal amplitude have been widely described during repeated muscle efforts (Moritani, Muro, and Nagata 1986), although the evidence is not conclusive. Decrements in EMG amplitude (e.g. root mean square, RMS) (Walker et al. 2013; Linnamo, Häkkinen, and Komi 1997) and increments in median frequency ($F_{\text{med}}$) (Linnamo et al. 2000) have also been reported during resistance training protocols involving various loading conditions. The inconsistent evidence and the stationarity issues of the EMG signals recorded during dynamic contractions (Farina 2006) have led researchers to keep searching for new spectral indices. Dimitrov et al. (2006) proposed a low to high-frequency ratio index ($FI_{\text{nsmk}}$), calculated as the ratio between the signal spectral moment of order (-1) and normalizing spectral moment of order $k = 2, 3, 4$, or 5. However, while $FI_{\text{nsmk}}$ seems to be more sensitive to detect fatigue compared to $F_{\text{med}}$ or RMS (Dimitrov et al. 2006; Gorostiaga et al. 2012; González-Izal, Rodríguez-Carreño, et al. 2010), no previous study has employed it in a specific power training context. Keeping in mind the task-specific nature of muscle fatigue development (Enoka and Duchateau 2016), it is important to consider specific power loading conditions and set-repetition schemes.

Previous investigations have reported large $F_{\text{med}}$ decrements and RMS increments of the EMG signal following fatiguing muscle efforts during the squat (Bonato et al. 2001), leg-press (González-Izal, Malanda, et al. 2010) and leg extension (Dimitrov et al. 2006) exercises. However, while these experimental set-ups are useful to better understand fatigue development, they do not directly translate to resistance training practices comprising ballistic exercises performed at maximal intended velocity (i.e. 4-6 repetitions per set and $> 3$ min rest between sets). For instance, the large muscle function impairments often reported during fatiguing protocols (i.e. ~50% decrease in maximum voluntary isometric force (Dimitrov et al. 2006) or ~45% decrease in power output (González-Izal, Malanda, et al. 2010)) are in contrast with the slightly impaired or even potentiated muscle function observed following a typical power training protocol (Brandon et al. 2015). Moreover, while the use of explosive stretch-shortening tasks is well extended in power training practices (Haff and Nimphius 2012) and may comprise task-specific fatigue mechanisms (Strojnik and Komi 1998; Chimera et al. 2004), these have been hardly employed in previous investigations.

## 1.3 Mechanisms underpining training induced increased strength

From the brain to the muscle, increasing research is elucidating the multiple neural and structural adjustements underpinining training induced strength gains (Folland and Williams 2007). However, while these adaptations may be commonly observed after general resistance training approaches, specific adaptations may occur following different resistance training orientations, such as power or explosive training. This section provides an overview of the main neuromuscular mechanisms mediating training-induced strength gains (more detailled reviews may be found in the literature: (Sale 1988; Semmler and Enoka 2000; Aagaard and Thorstensson 2003; Aagaard 2003; Folland and Williams 2007)).

### 1.3.1 Neural adaptations

The key role of neural mechanisms has been highlighted in multiple situations where strength changes are observed without meaningful variations in muscle structure (e.g. early variations in muscle strength following training, detraining or injury periods) (Sale 1988). Likewise, the cross-over training phenomenon (i.e. training one limb leads to contralateral improvements; (Zhou 2000)) and the strength gains achieved through imagery interventions (Yue and Cole

1992) provide further evidence for the importance of neural adaptations.

Increased maximal activation of agonist muscles has been often observed following resistance training (Häkkinen, Alén, and Komi 1985; Fernandez del Olmo et al. 2006; Balshaw et al. 2017). Greater surface EMG amplitude during maximal efforts (Balshaw et al. 2017) and increases in maximal activation levels measured using the interpolated twitch technique (i.e. maximal peripheral nerve stimulation during a MVIC) (Knight and Kamen 2001) suggest an increased efferent neural drive reaching the agonist muscles. Other investigations have examined the relationship between isometric force and surface EMG amplitude to explore changes in changes in the activation of agonist muscles. Following training, greater force levels for the same agonist EMG activation suggest improved muscle contractile properties (i.e. hypertrophy) (Garfinkel and Cafarelli 1992; Narici et al. 1996). Conversely, similar EMG-force relationship and increased MVIF would suggest central adaptations as responsible for strength changes. A decreased electrical activity of the antagonist muscles may also mediate gains in net force output. Notwithstanding, studies have reported conflicting results (Erskine et al. 2010; Balshaw et al. 2017) and the biomechanically challenging demands of real life athletic movements may imply a more complex interplay between agonist, antagonist and synergist muscles (Martinez Valdes et al. 2018).

At the motor unit level, strength training increases the frequencies at which MUs discharge action potentials (Duchateau, Semmler, and Enoka 2006), which are of particular relevance for controlling muscle force (Enoka and Duchateau 2017). While the MU recruitment "size principle" seems to remain unchanged (Henneman 1957), greater discharche frequency rates and lower recruitment thresholds have been reported after strength training (Van Cutsem, Duchateau, and Hainaut 1998; Kamen and Knight 2004; Christie and Kamen 2010). These changes at the MU level could be mediated by both, an enhanced intrinsic capacity of the MUs to travel action potentials (Gardiner, Dai, and Heckman 2006) and changes in the synaptic input received. Importantly, the key role of cortical and spinal neural networks leading to increased neural drive is being progresivelly elucidated.

Increments in the Hoffman (H) reflex, measured during maximal isometric efforts, have been reported following a 14-week heavy resistance period (Aagaard et al. 2002a) and 4-week plyometric training program (Voigt, Chelli, and Frigo 1998), suggesting an enhanced neural drive due to reduced afferent inhibition. As regards the cortical adaptations, increasing investigations from the neurosciences field have described their central role, particularly at the early stages of skill adquisition (Doyon and Benali 2005; Classen et al. 1998). Despite the conflicting research on the particular influence of corticospinal excitability on the training-induced strength gains (Jensen, Marstrand, and Nielsen 2005), increasing research is elucidating the specific corticospinal changes underlying strength training adaptations (e.g. reduced intracortical inhibition and cortical silent period duration, rather than changes in corticospinal excitability) (Kidgell et al. 2017).

### 1.3.2 Structural adaptations

On the morphological side, both quantitative and qualitative changes in the components of the MTU are also known to be key mediators of changes in strength. Increments in CSA at both the fiber and muscle levels have been usually described and are known to be of key relevance for maximal isometric strength production (Folland and Williams 2007). The increased contractile material after training facilitates force production by increasing the number of cross-bridges (Bamman et al. 2000), although increasing research shows that this hypertrophic response can be region-specific (Earp et al. 2015), entailing other implications for the biomechanical function of the MTU.

The arrangement of muscle fibers in relation with connective tissues (i.e. tendon, aponeurosis) seems to provide a relevant mechanical influence on the muscle maximal tension and shortening velocity (Narici, Franchi, and Maganaris 2016). Greater pennation angles have been reported in more hypertrophied muscles (Blazevich 2006) and seem to reflect increments in the muscle contractile material. Conversely, longer muscle fibers (i.e. more sarcomeres in series) have been proposed to allow for greater skeletal muscle shortenig velocity and muscle power (Aagaard et al. 2001; Blazevich 2006). Notwithstanding, despite of the evidence, these results come mostly from static, region-specific muscle architecture measurements and the implications for muscle performance during dynamic muscle function are not fully understood (Dick and Wakeling 2017).

Other biomechanical factors, comprising the active and passive (Klinge et al. 1997; Ryan et al. 2009; Blazevich 2018) mechanical properties of the MTU also underlie strength gains. Despite the methodological challenges, increasing research is elucidating the role of enhanced connective force transmission (Kjaer 2004; Magnusson et al. 2008; Jakobsen et al. 2016; Magnusson and Kjaer 2018) and elastic energy storage-release (Roberts 2016).

## 1.4 Altitude training

Albeit similar $O_2$ content at sea level and high altitude, the decreasing partial pressure of atmospheric oxygen at altitude triggers immediate respiratory, cardiovascular and metabolic responses that eventually impact the skeletal muscle function (Bärtsch and Saltin 2008). Induced by the increased hypoxia-induced sensitivity of the peripheral chemoreceptors, the hyperventilation response helps to compensate the drop in arterial oxygen saturation. The often less humid and cold conditions found at high altitude, along with the hyperventilation response, contribute to a reduced plasma volume (minimized when euhydrated), affecting the blood haemoglobin concentration and other cardiovascular parameters (Bärtsch and Saltin 2008). Among other physiological responses, these acclimation respiratory and cardiovascular adaptations occurring at altitude have been known for a long time to mediate impairments in endurance performance (Wehrlin and Hallén 2006) and acclimation following prolonged altitude exposure (Bärtsch and Saltin 2008). However, as suggested by Evans and Consolazio more than 50 years ago (Evans and Consolazio 1967), the influence of exposure to higher altitudes on human performance is dependent on the type of effort performed. Indeed, unlike endurance performance, the nervous system ability to control and maximally activate muscles during isolated maximal isometric efforts has been shown to be preserved, even at altitudes greater than 5000m (Perrey and Rupp 2009).

### 1.4.1 Hypoxic levels, types and training strategies

Before discussing the specific scientific literature concerning the hypothetical interaction between altitude and strength training adaptations, it seems essential to have an overview of the different types and levels of hypoxia that set the ground for the altitude training strategies commonly used in elite sport. Importantly, the inherent differences between hypoxic modes (e.g. hypobaric *vs.* normobaric), levels (e.g. high altitude *vs.* moderate altitude) and training strategies (e.g. living and training at altitude *vs.* intermittent exposure) should be carefully considered when examining the training adaptive response.

#### Types of hypoxia

Environmental hypoxia, achieved by either natural (altitude) or simulated procedures, is considered to occur when a decrement in the $PO_2$ of the inspired air goes below 150 mmHg (Farrell, Joyner, and Caiozzo 2012). A normobaric hypoxic condition may be achieved by either a reduction in the inspired $O_2$ content or through nitrogen-enriched air. Hypobaric hypoxia, although it can be artificially simulated (Garner et al. 1991), is generally considered from 500 m above sea level (Bärtsch and Saltin 2008) and is caused by a decrement in barometric pressure. Importantly, while both hypoxic conditions eventually limit the oxygen delivery to the muscle tissue, the underlying cascade-like process may differ at some point. Although the specific underlying mechanisms are unclear and a matter of debate (Millet, Faiss, and Pialoux 2012; Millet, Faiss, and Pialoux 2013), an increasing body of evidence shows significant differences in the functional and physiological responses following exposure to hypobaric hypoxia (HH; $FiO_2 = 20.9\%$; $BP < 760$ mmHg) *vs.* normobaric hypoxia (NH; $FiO_2 < 20.9\%$; $BP = 760$ mmHg) (Conkin and Wessel 2008).

Greater hyperventilation (Savourey et al. 2003; Saugy et al. 2014) and lower $SaO_2$ levels (Saugy et al. 2014) have been reported under hypobaric hypoxia, suggesting a likely greater efficacy for altitude training adaptations compared to normobaric hypoxia (Millet, Faiss, and Pialoux 2012; Saugy et al. 2014). A reduction in barometric pressure may also affect fluid dynamics, potentially affecting vasoconstriction and other cardiovascular-related responses regulated by the central nervous system (Conkin and Wessel 2008). Moreover, different effects on neuromuscular performance have been suggested, with studies observing greater impairments in postural stability (Degache et al. 2012) and improvements in dynamic strength performance under hypobaric hypoxic conditions (Young et al. 1980; Feriche et al. 2014). Importantly, the reduced air density at higher altitudes (i.e. $> 1500$ m) has been also suggested to play a key role in the performance enhancement during sprints (Peronnet, Thibault, and Cousineau 1991; Arsac 2002) and other high-velocity running and jumping athletic tasks (Hamlin, Hopkins, and Hollings 2015). Indeed, the specific physiolgical and physical consequences of exposure to higher altitudes are known to depend on the hypoxia severity and duration (i.e. hypoxic dose). Careful attention should be thus paid when it comes to investigating the potential effects of different altitude training strategies on the short and long-term responses.

### Level of hypoxia

The progressive decrease in the $O_2$ partial pressure with altitude is responsible for the magnitude of the adaptive responses (Bärtsch and Saltin 2008). Both exposure duration and hypoxic level are key elements affecting the hypoxic dose that may influence training responses (Millet et al. 2017). While the main acclimation physiological responses may be shared across altitude levels (Bärtsch and Saltin 2008), their varying time course and severity are of practical importance for the organization of the training load.

Acute mountain sickness symptoms are likely minimized at moderate altitude, where athletes usually carry out their training camps (Millet et al. 2010). Normobaric hypoxia studies have reported a shift in the neuromuscular mechanisms underlying fatigue development, from peripheral to central, as altitude increases (Goodall et al. 2011). In this context, the interplay between the magnitude of altitude levels, the physiological responses and training demands have generally made “moderate altitude” an optimal level for training purposes, at least in the traditional altitude training strategies comprising prolonged altitude exposures.

Different places over the world have emerged to provide athletes with altitude training conditions, although these remain scarce. Table 1.1 provides an overview of the principal altitude training centres in the world (Millet et al. 2010). Notwithstanding, the number of centres providing logistical support to different sports remains scarce. The often long travelling distances from sea level to the altitude training place limit the possibility to use training strategies comprising different altitude levels, or intermittent exposure. In this context, the Sport Performance Centre of Sierra Nevada, located at 2320 m above sea level in Southern Spain, provide unique training conditions. Its proximity to sea level conditions favours the possibility to easily alternate training and living at different altitude levels. Indeed, the potential practical interest of alternating hypoxic and normoxic conditions during training has motivated the technical development and research on the use of portable and inflatable simulated hypoxic conditions (Girard, Brocherie, and Millet 2013).

**Table 1.1:** Altitude training places around the world. Adapter from Millet et al. (2010).

| Location | Country | Altitude (m) |
|---|---|---:|
| Prémanon | France | 1200 |
| Thredbo | Australia | 1350 |
| Crans-Montana | Switzerland | 1500 |
| Albuquerque | USA | 1500 |
| Potchefstroom | South-Africa | 1550 |
| Snowfarm | New Zealand | 1560 |
| Pretoria | South-Africa | 1750 |
| Boulder | USA | 1780 |
| Ifrane | Morocco | 1820 |
| St. Moritz | Switzerland | 1820 |
| Font-Romeu | France | 1850 |
| Colorado Springs | USA | 1860 |
| Kunming | China | 1860 |
| Belmeken | Bulgaria | 2000 |
| Eldoret | Kenya | 2100 |
| Flagstaff | USA | 2130 |
| Sierra Nevada | Spain | 2320 |
| Iten | Kenya | 2350 |
| Addis Ababa | Ethiopia | 2400 |
| Bogota | Colombia | 2640 |
| Quito | Ecuador | 2740 |
| La Paz | Bolivia | 3600 |

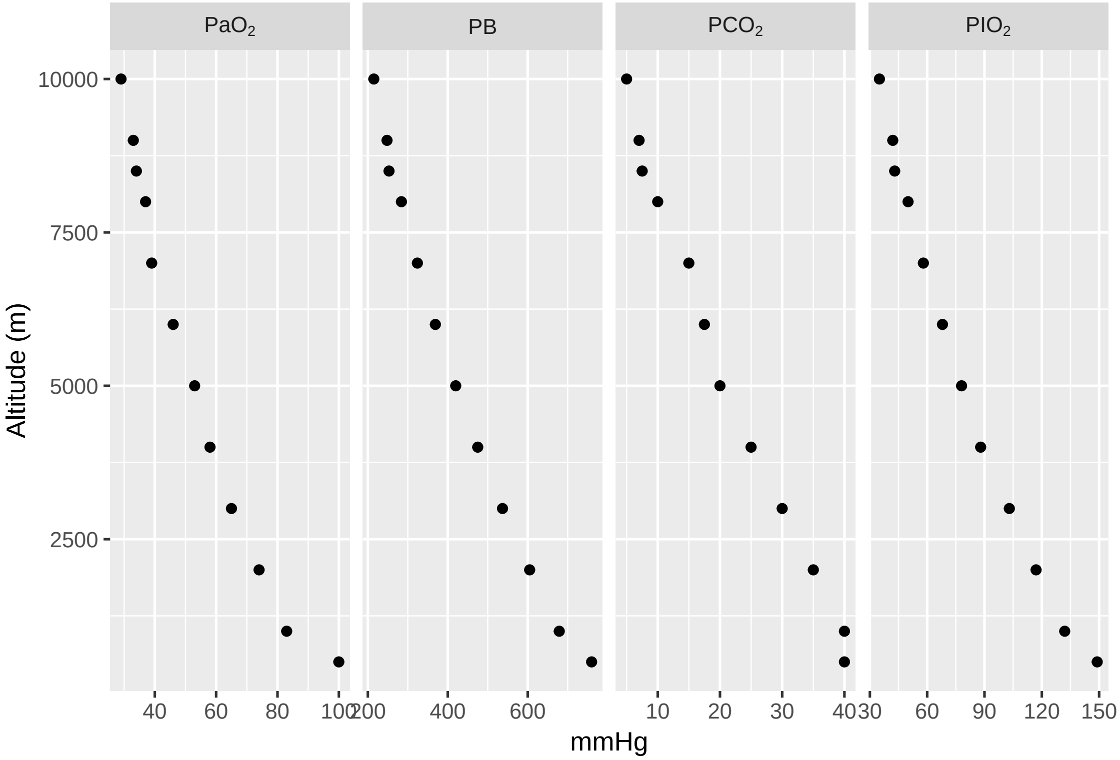

**Figure 1.7:** Relationship between altitude (m) and barometric pressure (PB), estimated partial pressure of inspired oxygen (PIO$_2$), estimated partial pressure of carbon dioxide (PCO$_2$), estimated partial pressure of alveolar oxygen (PaO$_2$); adapted from Leissner et al. (2009).

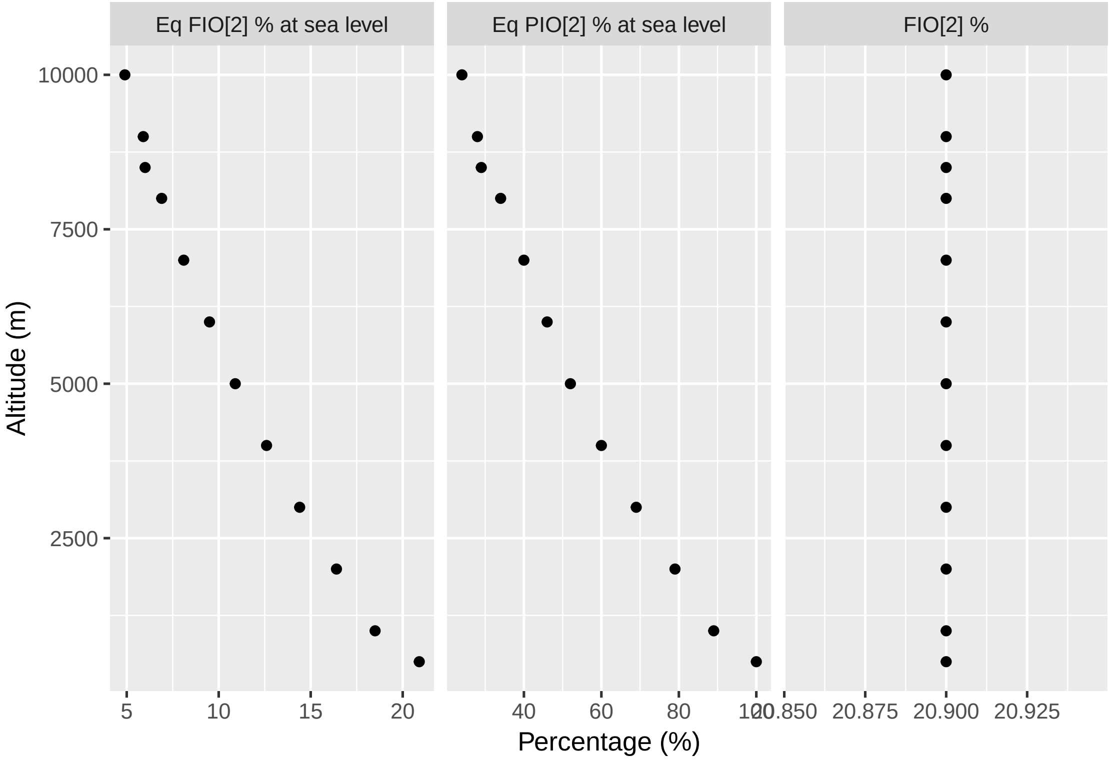

**Figure 1.8:** Relationship between altitude (m) and inspired oxygen concentration ($FiO_2$; %), equivalent of the $PIO_2$ in percent at sea level (Eq $PIO_2$) and equivalent of the FiO2 at sea level (Eq $FiO_2$); adapted from Leissner et al. (2009).

### Hypoxic training strategies

The possible combinations of hypoxic modes (i.e. hypobaric and normobaric) and levels during training and living periods encourage the development of multiple training strategies aiming to enhance sea-level performance or acclimation to perform at altitude.

The early developed altitude training strategy *"Live High, Train High"* (LHTH) usually comprises a 2 to 4-week moderate altitude stay and is a widely extended practice among elite endurance atheltes. Other strategies such as the *"Live High, Train Low"* (LHTL) were then proposed to maximize training intensity under normoxic conditions while maintaining the potentially positive haematological advantage of staying at altitude (Millet et al. 2010). Despite the multiple scientific studies carried out, the high variable individual training responses along with the methodological challenges continue feeding the debate about the statistical and/or practical advantages of altitude training for sea level endurance performance (Brocherie and Millet 2018).

Altitude training research activity has progressively evolved from a general "haematological" purpose, towards the use of specific hypoxic strategies according to the physiological determinants of different sport disciplines (Faiss, Girard, and Millet 2013). For example, considerable research has been recently carried out concerning the ability to repeat intermittent efforts, a determinant factor in multiple disciplines such as racket, combat and team sports (Girard, Brocherie, and Millet 2017). On this purpose, altitude training strategies comprising a hypoxic environment only during training (i.e. intermittent hypoxic training strategies) have been highlighted (Millet and Girard 2017), to target improvements in other metabolic and neural adaptations.

On the whole, the use of hypoxia in sport is being extended to a broader scope embracing not only enhancement of endurance performance but also neuromuscular aspects (Brocherie et al. 2015; Scott, Slattery, and Dascombe 2014). The increased metabolic and neural stress during training could mediate physiological adaptations related with an improved use of energy production comprising neural, morphological and molecular muscle adaptations. An overview of the different altitude training methods arising from combining hypobaric and normobaric hypoxia is shown in Figure 1.9. While there are multiple combinations, research is yet to elucidate their effectiveness compared to the same stimulus under normoxic conditions.

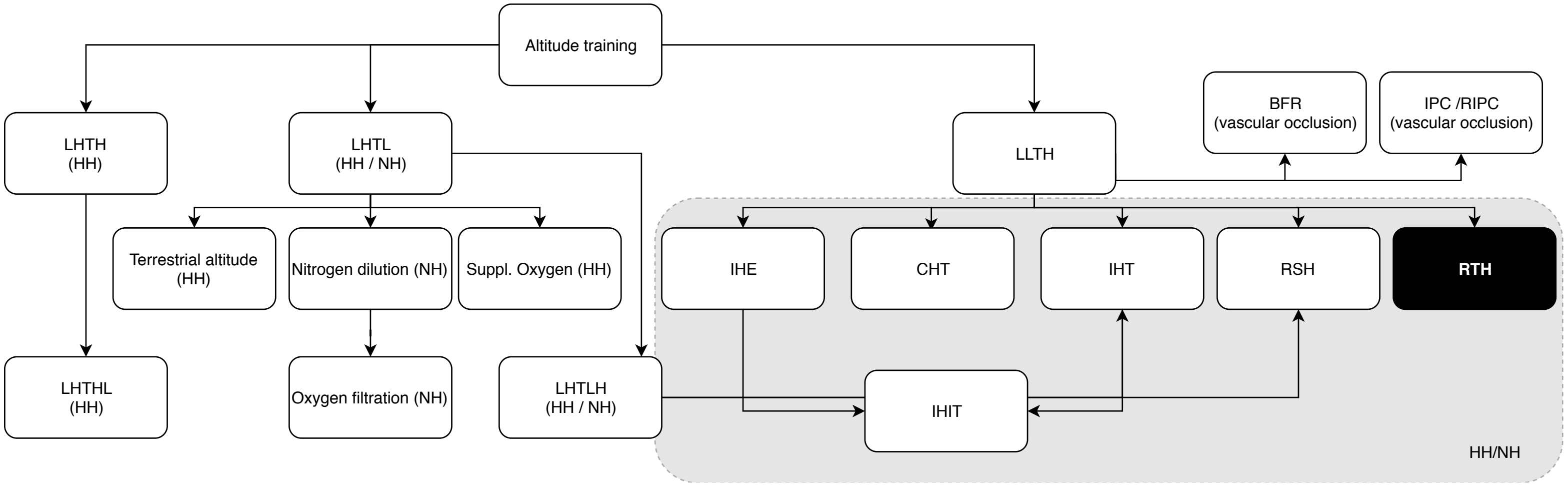

**Figure 1.9:** Adapted from Millet et al. (2015) and Girard, Brocherie, and Millet (2017). LHTH, "live-high, train-high"; LHTHL, "live-high, train-high and low"; LHTL, "live-high, train-low'; LHTLH,"live high-train low and high"; LLTH,"live low, train high"; IHE, intermittent hypoxic exposure; CHT, continuous hypoxic training; IHT, interval hypoxic training; RSH, repeated sprint training in hypoxia; RTH, resistance training in hypoxia; IHIT, IHE during interval-training; NH, normobaric hypoxia; HH, hypobaric hypoxia; BFR, blood flow restriction; IPC, ischemic pre-conditioning; RIPC, remote ischemic pre-conditioning. Other systemic hypoxia methods may comprise $CO_2$ absorption rebreathing with a mask or voluntary hypoventilation at low lung volume.

## 1.5 Environmental hypoxia and neuromuscular performance

The acute, short-term and prolonged effects of passive hypoxic exposure on the nervous system function have been previously explored through different neuromuscular assessment procedures (Amann and Kayser 2009; Marillier et al. 2017). From the first hours at altitude, an overactivation of the sympathetic nervous activity has been usually observed, which is believed to mediate some of the earliest respiratory and cardio-vascular adjustments such as hyperventilation or vasoconstriction (Hansen and Sander 2002). Experimental data showing increased adrenergic activity and efferent neural discharge to the skeletal muscle has been reported (Hansen and Sander 2002; Seals, Johnson, and Fregosi 1991; Katayama et al. 2011). However, while this overactivation response may be even further potentiated with exercise (Seals, Johnson, and Fregosi 1991; Katayama et al. 2011), the functional implications for motor performance remain conflicting. While unchanged maximal isometric force has been usually reported at higher altitudes (Perrey and Rupp 2009), other investigations have reported enhanced upper- (Young et al. 1980; Feriche et al. 2014) and lower-body (García-Ramos, Štirn, et al. 2016) strength performance of the under acute hypobaric but not normobaric (Feriche et al. 2014; Scott et al. 2015) hypoxic conditions.

Different methodological paradigms, comprising voluntary and evoked contractions, have been employed to evaluate potential acute alterations in the muscle contractile properties, neural excitability or synaptic neurotransmission and their acclimation to prolongued altitude exposure. However, while some investigations provide evidence for changes in central (Millet et al. 2009), peripheral (Katayama et al. 2007) and other neural circuits concerning the sensorimotor control of skeletal muscles (i.e. afferent neural activity, spinal and cortex excitability), these do not come without methodological concerns (Finn, Gandevia, and Taylor 2018; Ruggiero et al. 2018) and conflicting effects at the functional level.

### 1.5.1 Acute responses

Unlike endurance performance (Fulco, Rock, and Cymerman 1998), previous investigations have shown that maximal voluntary force production is preserved at high altitude (Eiken and Tesch 1984; Garner et al. 1991; Fulco et al. 1994; Fulco et al. 1996; Katayama et al. 2007; Szubski, Burtscher, and Löscher 2007). Similar force and muscle activation levels have been observed during maximal voluntary isometric contractions performed under different hypoxic conditions. Likewise, force production during electrically elicited contractions (i.e. twitch force) has been shown to remain unchanged under simulated hypobaric (Garner et al. 1991) or normobaric (Katayama et al. 2007) hypoxic conditions.

Other research has reported increased strength performance following acute altitude exposure. In 1980, Young et al. (1980) reported meaningful improvements (13.3%) in upper-body isometric strength following 48h of simulated altitude (i.e. hypobaric hypoxia; 4572m), although unchanged strength performance (i.e. isometric or isokinetic) was observed at earlier time points (i.e. 2h, 24h). Compared to normoxic conditions, other investigations have found improvements in muscle strength performance during isolated, dynamic explosive movements performed under hypobaric but not normobaric conditions (Feriche et al. 2017). Feriche et al. (2014) reported a ~3% increment in the loading condition associated with peak power output, and a ~6% 1RM improvement assessed during a progressively loaded bench-press test at moderate altitude compared to normobaric hypoxic or normoxic conditions. Likewise, Garcia-Ramos et al. (2016) also observed improvements in strength performance at moderate altitude. Specifically, greater values of maximal theoretical velocity and power, obtained during a loaded squat jump force-velocity test, and mechanical performance during unloaded countermovement jump were reported. These findings are in line with the greater sprinting and jumping maximal performances often observed at moderate terrestrial altitudes (Hamlin, Hopkins, and Hollings 2015). Notwithstanding, while both reduced air density and activation of the nervous system function could explain these acute improvements, no direct experimental mechanistic evidence is available, and the significance for strength training adaptations remains yet to be investigated.

Within the context of fast force development, the afferent and efferent neural coupling of the nervous system becomes more revelant and specific hypoxic effects could be suspected. Nonetheless, conflicting evidence is available regarding the influence of altitude exposure on the spinal and supraspinal neural excitability. At the spinal level, both increased (Delliaux and Jammes 2006), decreased (Willer, Miserocchi, and Gautier 1987) and unchanged (Kayser, Bokenkamp, and Binzoni 1993; Garner et al. 1991) H-reflex recordings have been described. From mild to severe normobaric hypoxic 10-minute exposure, unchanged neuromuscular function and cortical voluntary activation have been reported (Goodall et al. 2011). On the contrary, Szubski and colleages (2006), using EMG recordings on the first dorsal interosseus muscle, reported that 45-min exposure to acute normobaric hypoxia ($FiO_2 = 0.12$) resulted in increased cortical excitability but unchanged functional performance. In fact, despite multiple research on the nervous system responses to hypoxia, the functional implications for muscle force production remain rather limited (Perrey and Rupp 2009).

### Neuromuscular fatigue

Exercise-induced fatigue development has been another tipically researched area concerning the effects of altitude exposure on neuromuscular performance. Different paradigms comprising both voluntary and evoked repeated contractions have been used to explore how the neuromuscular adjustments underpinning exercise-induced motor impairments may be influenced by environmental hypoxia. From a reduced descending neural drive (i.e. central factors) to an impairment in the contractile properties of muscle fibres (i.e. peripheral factors), different mechanisms could play a role in muscle fatigue, although once again the evidence is conflictive.

Compared to normoxic conditions, Eiken and Tesch (1984) reported a greater decline in peak torque during continuous knee extension repetitions in normobaric hypoxia ($FiO_2 = 0.11$); a reduced time to exhaustion during an sustained isometric contraction of the knee extensors (at 27% MVIC) was also observed. Similar results were reported by Fulco et al. (1994), who observed greater time to exhaustion and reductions in MVIC during repeated

5-s adductor pollicis contractions at 4300 m of altitude. While these findings suggest an increased neuromuscular fatigue development during isolated repeated muscle contractions under hypoxic conditions, the particular involvement of peripheral and/or central factors is source of debate.

By comparing force and myoelectrical signals recorded during both voluntary and electrically evoked contractions, specific functional information about central and peripheral factors of the neuromuscular system may be obtained (Merton 1954; Vøllestad 1997). Greater peripheral fatigue under hypoxic conditions has been suggested from studies showing a faster rate of twitch isometric force decrement during evoked, compared to voluntary contractions. Katayama et al. (2007) reported that three sets of nine intermittent isometric contractions of the knee extensors under normobaric hypoxia ($FiO_2 = 0.11$) resulted in greater twitch force decrements and increments in the surface EMG signal amplitude. Similarly, Felici et al. (2001) also observed reduced time to failure and greater EMG-signal derived myoelectrical fatigue symptoms when performing a sustained isometric contraction of the elbow flexors at 5050 m of altitude. Although several mechanisms could mediate an hypoxic-induced impairment of the muscle contractile properties during fatiguing contractions, other studies have suggested oposite findings: preserved muscle contractile properties but an impairment in the neural drive descending from supraspinal regions.

Degens et al. (2006) showed that endurance time during a voluntary sustained isometric knee extension at 30% MVIC was reduced in normobaric hypoxia (~4000 m), but no altitude effects were observed when the repeated contractions were electrically elicited. Similarly, other investigations have provided evidence for greater central fatigue symptoms during fatiguing continous (Casale et al. 2004) and intermittent (Millet et al. 2009) isometric strength protocols conducted at high altitude (Casale et al. 2004) or normobaric hypoxia ($FiO_2 = 0.11$; (Millet et al. 2009)) conditions. These findings support the hypothesis that exercise-induced (i.e. isometric, single-joint tasks) functional impairments are greater under hypoxic conditions. Notwithstanding, the consequences of these changes on motor unit recruitment strategies or long term resistance training adaptations remain underexplored.

Indirect evidence suggests that repeating muscle contractions under hypoxic conditions could impact muscle fibre recruitment. For example, two studies have reported greater twitch force after a fatiguing protocol under normobaric hypoxia ($FiO_2$ 0.12 - 0.15) compared to normoxic conditions (Dousset, Steinberg, et al. 2001; Szubski, Burtscher, and Löscher 2007). Notwithstanding, the mechanisms and extent to which these physiological responses may interfere with resistance training practices remains yet to be investigated. There exist *in vitro* evidence showing reduced sensitivity of the type III and IV muscle afferents under hypoxic conditions (Arbogast et al. 2000; Dousset, Decherchi, et al. 2001). Considering the implication of III and IV muscle afferents in the recruitment of oxidative (i.e. type I) skeletal muscle fibres, a selective recruitment of type II (i.e. glucolitic, fast) fibres may be facilitated under hypoxic and fatiguing conditions, although direct evidence is lacking.

Several ideas may be considered as regards the role of limited $O_2$ availability on performance fatigability. The fact that intramuscular pressure during muscle contraction also leads to an ischeamic condition may be an important counfounding factor, notably during continuous isometric contractions. Dynamic contractions comprise variations in muscle architecture and intra-muscular pressure (Dick and Wakeling 2017) that could imply different neural and metabolic fatigue consequences. Also, regardless of the environmental condition, it is important to keep in mind that the mechanisms underpinning fatigue are highly task dependent (Enoka and Duchateau 2016). Despite constant efforts to discern specific responses of the nervous system under hypoxic conditions (Goodall 2017; Ruggiero et al. 2017), there remain methodological (Finn, Gandevia, and Taylor 2018; Ruggiero et al. 2018) and conceptual (Enoka and Duchateau 2016) concerns around the complex task of fatigue assessment. Accordingly, the exploration of typical exercises and repetitions schemes commonly used in sport contexts seems warranted to maximize transfer to the field.

### 1.5.2 Chronic responses

The influence of prolonged altitude exposure, without systematic physical training, on the neural and molecular adaptations of the neuromuscular system have been also matter of research (Bärtsch and Saltin 2008). Prolonged exposure to altitude has been shown to restore the excitability of the brain-to-muscle pathway (Goodall, Twomey, and Amann 2014), which may mediate an improvement in exercise tolerance at altitude (Ruggiero et al. 2017). At the skeletal muscle tissue level, biopsy experiments have revealed that prolonged hypoxic exposure can lead to an upregulation of proteins involved in the muscle cells acid-base control such as the transport of bicarbonate, hydrogen ions and lactate across the membrane (Juel et al. 2003). Other experiments have described a reduction in the CSA of muscle fibres following prolonged hypoxic exposure. While a potentially negative effect of hypoxia on muscle morphology could be suspected (D'Hulst and Deldicque 2017), other research has demonstrated that when nutrition, sleeping and physical activity habits are carefully controlled, hypoxia-induced changes in muscle morphology can be reduced (Butterfield et al. 1992).

Using computer tomography, Ferreti et al. (1990) reported a 12% decrease in thigh CSA after a three-week altitude expedition to the Mount Everest. Atrophy responses to simulated extreme altitude were also reported by MacDougall et al. (1991) in six male who underwent a 40-day progressive decompression protocol; decreases in CSA at both fiber (biopsy) and muscle levels (computer tomography) were also reported. These findings have been commonly described in the literature examining changes in the muscle fibers morphology of mountaineers going to altitude (Hoppeler and Vogt 2001).

Following a 40-day period of simulated hypobaric hypoxia exposure, Garner et al. (1991) reported no changes in the maximal voluntary isometric strength of the ankle dorsiflexors. On the contrary, neuromuscular fatigue symptoms were observed from greater force decrements during electrical stimulation of the ankle dorsiflexors. Fulco et al. (1994) observed that a 20-day exposure to 4300 m did not affect the maximal voluntary isometric force of the adductor pollicis muscle and improved the maximal sustained time performing isometric contractions at 50% MVIC. While such findings are of great value to better understand the neuromuscular responses and mechanisms mediating acclimation to high altitude, the practical implications for strength training contexts is limited. Athletic movements and strength training practices imply specific tasks, intensities and contraction types that could concern different acute and long term adjustements to higher altitude exposure. Studies

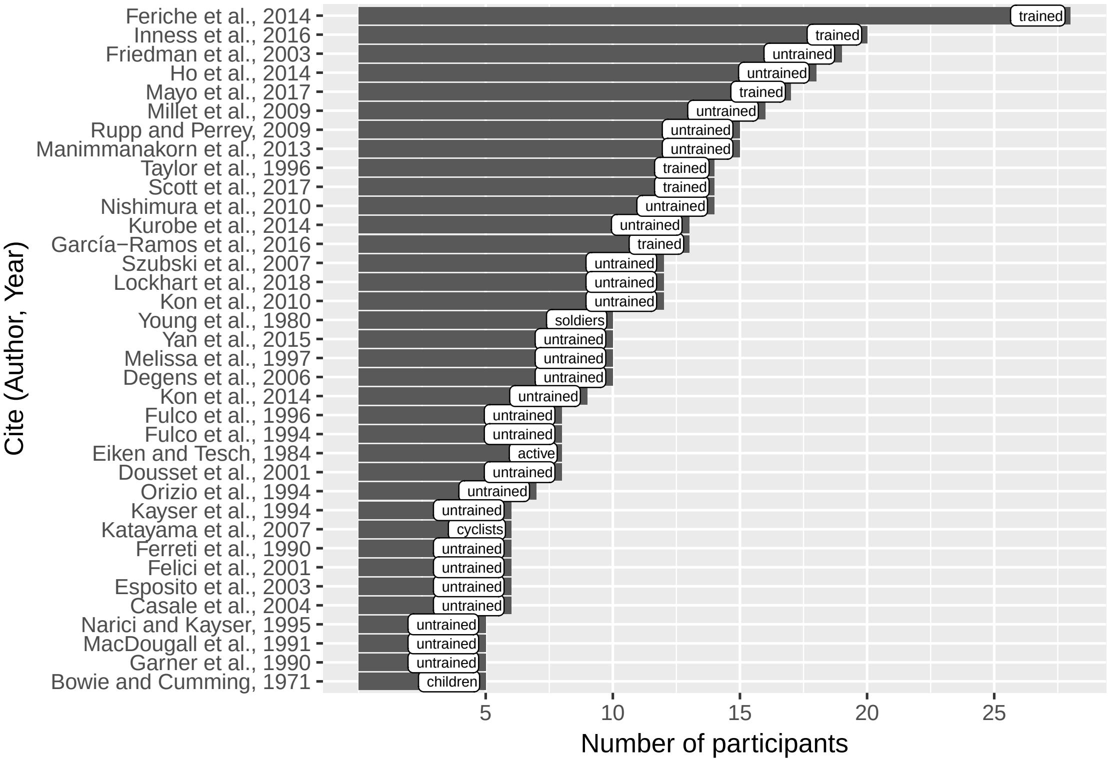

**Figure 1.10:** Number of participants included in previous investigations concerning neuromuscular and resistance training experiments (total number of participants from all experimental conditions).

exploring the muscle skeletal adaptations to altitude exposure have mostly focussed on the passive acclimation process, without considering the influence of strength training. Moreover, it should be kept in mind that the extreme altitude and logistic-related aspects of high altitude expeditions significantly differ from sport-related altitude training camps conditions where nutrition, sleep and training tools are usually considered. Indeed, scientific experiments during high altitude expeditions have usually comprised small sample populations (Figure 1.10) at very high altitude levels (Figure 1.11).

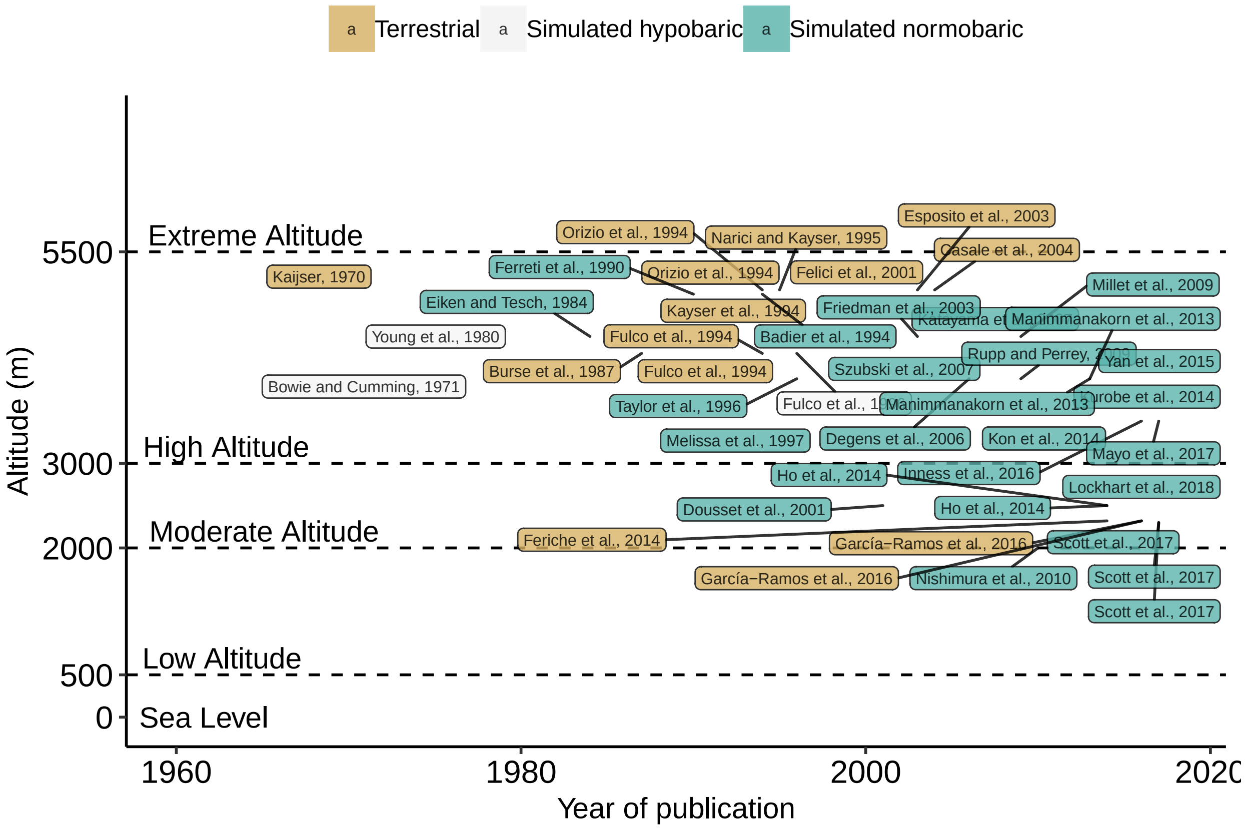

**Figure 1.11:** Timeline of published expermients concernig neuromuscular performance and strength measurements at different altitude levels and type of hypoxic stimulus (i.e. hypobaric or normobaric hypoxia).

Another important difference between studies is the task and muscle group assessed. Interestingly, many neuromuscular research studies conducted under conditions of high altitude have focussed on very isolated tasks such as elbow (Orizio, Esposito, and Veicsteinas 1994; Casale et al. 2004; Esposito et al. 2003), wrist (Bowie and Cumming 1971; Caquelard et al. 2000; Dousset, Steinberg, et al. 2001) or finger (Fulco et al. 1994; Badier et al. 1994) movements. While these tasks provide sound experimental conditions to rule out the potential respiratory related hypoxic effect, and allow to focus on the neural aspects (Kayser et al. 1994), their traslation to complex athletic tasks is likely limited. Common strength training exercises (i.e. squats, deadlifts, plyometric drills) comprise larger muscle mass and more complex muscle function (i.e. stretch-shortenig cycles). As suggested above, this idea may also be of further relevance when it comes to assessing the role of hypoxia in the rate of fatigue development given that both the magnitude and underlying mechanims of performance fatigability are known to be highly task specific (Enoka 1995).

Despite scarce evidence for functional changes in the neuromuscular function, findings from high-altitude expeditions focussed on the neuromuscular acclimation responses highlight the highly adaptive capacity of the neuromuscular system to hypoxia. Its interaction with different resistance training methods, demanding both peripheral and central factors, remains largely unexplored and constitutes a relevant area of research in elite sport. Only in recent years the scientific literature has started to develop concerning the influence of training strength under hypoxic conditions on the functional and physiological adaptations (Scott, Slattery, and Dascombe 2014; Feriche et al. 2017). Nonetheless, most of the studies conducted up to date have comprised simulated hypoxic conditions, and little attention has been paid to the potential specific effects of explosive, high-velocity resistance training actions comprising stretch-shortening cycles (SSC).

## 1.6 Resistance hypoxic training

Early hypotheses presenting altitude as a harmful environment for skeletal muscle development (Ferretti, Hauser, and di Prampero 1990; Narici and Kayser 1995), have been progressively challenged by the idea of using hypoxia to maximize muscle strength responses (Deldicque and Francaux 2013; Feriche et al. 2017). It has been suggested that combining systemic hypoxia during training and normoxia during recovery (i.e. intermittent hypoxic resistance training [IHRT]), could confer an advantageous stimulus to maximize the muscle adaptations following resistance training (Scott, Slattery, and Dascombe 2014). Moreover, while two to four-week altitude training camps are usually carried out in elite sport, an IHRT strategy could be used to target other training goals requiring longer adaptation periods (i.e. strength training related). Notwithstanding, the evidence stemming from studies exploring the influence of IHRT on muscle functional and physiological adaptations remains inconclusive and limited to normobaric hypoxic simulated conditions.

### 1.6.1 Hypertrophy-oriented resistance hypoxic training

In 1995, Narici and Kayser (1995) reported smaller arm CSA increments following a 1-month resistance training period in the Mount Everest (5050 m; 4 weekly sessions; 6 sets of 10 reps at 75% 1RM), compared to the same protocol performed at sea level. While these findings may suggest a reduced hypertrophic muscle response at permanent high altitude, other environmental factors often altered during high altitude expeditions (i.e. nutrition, sleeping and physical activity habits) should not be discarded (Bärtsch and Saltin 2008). In fact, later studies have shown that the hormonal and metabolic acute responses following resistance training may be increased under hypoxic conditions.

Kon et al. (2010) reported that five sets of 10 repetitions at 70% 1RM during the bench-press and leg-press exercises caused greater increments in blood lactate, serum growth hormone (GH), epinephrine and norepinephrine concentrations when performed under normobaric hypoxia (0.13% $FiO_2$) compared to normoxia. Similarly, a low-intensity resistance training protocol during the bench-press and leg press exercises (5 sets of 14 repetitions at 50% 1RM, 1 min rest between sets) under hypoxic conditions ($FiO_2 = 0.13$) resulted in greater GH concentrations (Kon et al. 2012). Kurobe et al. (2015) observed greater serum GH concentrations following elbow flexion-extension repetitions to failure under simulated environmental hypoxic conditions ($FiO_2 = 0.12$) than normoxia. Increased blood lactate concentrations and voluntary EMG activation during a back squat and deadlifts session (60% 1RM; 3 sets of 10 reps, 60s rest) were also described (Scott, Slattery, Sculley, Lockhart, et al. 2017) in moderate normobaric hypoxic conditions ($FiO_2 = 16\%$). However, although these findings support greater metabolic stress during hypoxic resistance training, no all studies have found meaningful differences.

Scott et al. (2017) reported no differences between normoxia, moderate ($FiO_2 = 0.16$) or severe normobaric hypoxia ($FiO_2 = 0.13$) in blood lactate concentration, RPE or muscle soreness following five sets of five repetitions of back squats and deadlifts at 80% 1RM. However, the minimal differences in muscle oxygenation (measured in the VL muscle) across conditions along with the maximal strength-oriented protocol (5 sets of 5 reps) and resting periods between sets (3 min) may explain the reported lack of differences in metabolic stress and neuromuscular responses. Similarly, no effects of normobaric hypoxia ($FiO_2 = 0.15$) were observed during a leg-extension training session (5 sets of 10 reps) on RPE, voluntary EMG activation or muscle oxygenation (measured using Near-infrared spectroscopy), regardless of the between-set resting period length used (1 min *vs.* 3 min) (Lockhart et al. 2018). Although metabolite accumulation and the EMG signal amplitude may be increased following moderate load resistance exercise in moderate-level hypoxia (Scott, Slattery, Sculley, Lockhart, et al. 2017), the functional consequences are not different (Scott, Slattery, Sculley, and Dascombe 2017). Recent research suggests that a high-intensity (6RM) circuit training organization may help to increase the magnitude of hypoxic induced metabolic stress compared to normoxic conditions (Ramos-Campo, Rubio-Arias, et al. 2017a; Ramos-Campo, Rubio-Arias, et al. 2017b).

Taken toguether, these investigations suggest that although an increased metabolic stress may occur when training under hypoxic conditions, certain methodological training aspects such as involved muscle mass, training load, between-set rests and the exercise / effort organization are important and may explain the unconsistent evidence available regarding the long term training consequences.

### Training adaptations

The first scientific publication exploring the potential advantage of using an IHRT strategy to boost the adaptive responses found no meaningful effects on the strength and endurance strength adaptations following a 4-week low resistance knee extension program under normobaric hypoxia ($FiO_2 = 0.12$) (Friedmann et al. 2003). While no meaningful functional or muscle CSA changes between groups were observed, it should be kept in mind that strength adaptations are highly training-specific, and these findings should therefore only apply to the training stimulus explored (low-load, single joint work). In fact, contradicting results are available regarding the functional and morphological responses following a typical research resistance training protocol conducted under moderate normobaric hypoxic conditions. There are studies reporting both significant (A. Manimmanakorn, Hamlin, et al. 2013; Nishimura et al. 2010; Kurobe et al. 2015) and no meaningful effects (Friedmann et al., 2003; Ho et al., 2014; Kon et al., 2014) of IHRT on the muscle CSA.

Studies reporting a positive influence of a IHRT strategy:

- Nishimura et al. (2010) suggested greater functional and hypertrophic responses following 12 elbow flexion and extension training sessions over a 6-week period. Greater 1RM gains and muscle CSA were reported following the IHRT condition, although the time × group interactions are unclear from the statistical results provided in the manuscript.

- Manimmanakorn et al. (2013) also observed a positive influence of systemic simulated normobaric hypoxia ($FiO_2$ constantly adjusted to maintain arterial oxygen saturation at ~80%) on maximal isometric strength and endurance strength (i.e. repetitions to exhaustion and 30-s sustained isometric contraction) following a 5-week knee flexion-extension resistance training period at 20% 1RM. Greater gains in thigh CSA (+5.3%) and neural adaptations (i.e. ~14% decrease in EMG RMS during repetitions to exhaustion) were also reported in the hypoxic training group compared to normoxia.

- Kurobe et al. (2015) explored strength, morphological and hormonal responses following 24 training sessions (8 weeks, 3 sessions per week) of elbow extension at a workload of 10RM, under normoxic or moderate normobaric hypoxic conditions ($FiO_2 = 0.12$). A greater muscle CSA increase was reported in the IHRT group. Moreover, during the first and last training session of the 8-week training period, higher blood growth hormone concentrations were observed in the hypoxic condition and similar increases in blood lactate concentrations. However, no functional differences in terms of maximal strength were observed.

On the contrary, other investigations have reported no influence of limited systemic oxygen availability on the training responses:

- Intermittent hypoxic exposure ($FiO_2 = 0.15$) during six weeks of 3-weekly squat exercise training sessions (3 sets at 10RM, 2min rest) had no influence on 1RM squat gains compared with normoxic conditions (Ho et al. 2014).

- Regardless of the environmental condition, sixteen resistance training sessions (bench press and leg-press) over a period of eight weeks resulted in similar strength and muscle CSA changes, although endurance related functional and physiological markers were observed to a greater extent in the IHRT group ($FiO_2 = 0.14$) (Kon et al. 2014).

The fact that very different maximal strength testing methodologies have been previously used [i.e., isometric (A. Manimmanakorn, Hamlin, et al. 2013; Ho et al. 2014), isokinetic (Friedmann et al. 2003; Ho et al. 2014) and direct (Kon et al. 2014), or indirect (Nishimura et al. 2010) maximal dynamic strength)] could partially explain these inconsistencies. Moreover, little research has focussed on the potential neuromuscular adaptations underlying not only maximal but also explosive stength performance.

### 1.6.2 Power-oriented resistance hypoxic training

Although differences in crucial methodological aspects, such as the resting time between training sets, may influence the lack of agreement between IHRT studies reporting changes in muscle CSA, other constraints in the current literature also limit the translation of these findings to the field. Resistance training practices aiming to enhance athletic performance often comprise maximal intended explosive efforts leading to both training-specific structural (Blazevich et al. 2003) and neural adaptations (Buckthorpe et al. 2015). Most of the IHRT interventions, however, have been focused on hypertrophy-oriented single-joint exercises (Nishimura et al. 2010; A. Manimmanakorn, Hamlin, et al. 2013) without performing maximal intended efforts to enhance explosive muscle performance. Scarce research has comprised maximal strength (Scott et al. 2015; Inness et al. 2016) or power-oriented resistance training, and it has been always limited to normobaric conditions. Indeed, no studies have specifically comprised high velocity, power-oriented resistance training under conditions of hypobaric hypoxia. Although previous investigations have reported a positive influence of hypobaric hypoxa on isolated explosive dynamic strength performance (Feriche et al. 2014; García-Ramos, Štirn, et al. 2016), the long term training implications remain yet to be investigated. Inness et al. (2016) reported greater 1RM squat gains following 20 training sessions over 8 weeks under simulated hypoxic conditions ($FiO_2 = 0.14$). The slightly greater CMJ performance observed in the IHRT group, without meanigful changes in CSA, highlights the potential role of neuromuscular adaptations. A close examination of the force-velocity (FV) relationship, comprising performance assessment under multiple loading conditions (Jaric 2015), as well as specific maximal and explosive isometric strength assessments (Maffiuletti et al. 2016) may help to reach a better understanding of the effects of IHRT on muscle strength performance.

Improvements in sprinting and jumping performances have been usually observed at moderate altitude levels (Hamlin, Hopkins, and Hollings 2015) and have been largely attributed to the decreased air density. However, while the influence of decreased air density on the energetics of maximal short-distance running has been described (Peronnet, Thibault, and Cousineau 1991; Arsac 2002), no research has been conducted within the context of resistance training. Similarly, the extent to which moderate hypobaric hypoxia influence neural drive and motor unit behaviour during explosive contractions remains largely underexplored. Evidence for hypoxia-induced changes in the muscle contractile properties (Dousset, Steinberg, et al. 2001; Szubski, Burtscher, and Löscher 2007) and the myoelectric manifestations of muscle fatigue (Felici et al. 2001) is available. However, these investigations have comprised non-ballistic fatiguing muscle contractions, which may significantly differ from the explosive ballistic efforts (Van Cutsem and Duchateau 2005). Although a positive influence of low-load resistance hypoxic training on muscle activation has been reported (A. Manimmanakorn, Manimmanakorn, et al. 2013), power oriented resistance training may lead to specific neural (Balshaw et al. 2016) and structural (Blazevich et al. 2003) muscle adaptations.

## 1.7 Approach to the problem

As described above thoughout the literature review, the limited and conflicting research activity comprising strength training interventions under hypoxic conditions, encourages further work. Specifically, the influence of intermittent exposure to hypobaric hypoxia on power-oriented resistance training practices remains unexplored and sets the main objectives of this thesis.

While some studies have previously explored the influence of normobaric hypoxia on muscle activation during resistance training (Lockhart et al. 2018), a more exhaustive analysis of the interference surface EMG signal may provide a better understanding of the complex fatigue development process (Merletti, Lo Conte, and Orizio 1991; Dimitrov et al. 2006). Moreover, no current IHRT studies under hypobaric conditions have been pusblished in the scientific literature. A power-oriented training approach would help to better understand the specific functional and physiological adaptations and how these may be influenced by intermittent exposure to moderate altitude.

# Chapter 2

# Aims and hypotheses

## 2.1 General aims

The general objectives of the present doctoral thesis work were:

1. To investigate the influence of acute moderate altitude exposure during a power-oriented lower-body resistance training sesion.
2. To investigate the influence of intermitent acute exposure to moderate altitude on the short-term adaptations following power-oriented resistance training.

## 2.2 Specific aims and hypotheses

Specific objectives and hypotheses have been targeted in five separate experiments. First, three studies were developed in normoxic conditions to refine the methodology employed to investigate the influence of moderate altitude on the acute and short-term adaptations following strength training.

*Preliminary research*

1) **Chapter 3.1**. To investigate the effects of a traditional vs. cluster power training intervention on the maximal force, velocity and power lower-body capabilities. It was hypothesized that a power training period comprising cluster sets would lead to further short-term power performance improvements.

2) **Chapter 3.2**. To examine performance and electromyography (EMG) changes during a power training protocol comprising continuous or clustered set configurations. It was hypothesised that greater myoelectric manifestations of neuromuscular fatigue and greater power output decrements would be observed during the continuous compared to clustered set configurations.

3) **Chapter 3.3**. The aims of this investigation were 1) to explore the association of key parameters obtained from the FV relationship ($F_0$, $V_0$, $P_{max}$, slope) during a CMJ test with specific maximal and explosive isometric force performance during a single-joint knee extension test, and 2) to assess the influence of the quadriceps architecture and voluntary muscle activation on the FV profile parameters. We hypothesized that 1) maximal and explosive isometric force production, assessed with a single-joint simple task (i.e. maximal and explosive knee extension), would associate with $F_0$ and $V_0$ respectively, and 2) muscle architectural and neural activation factors would present meaningful associations to the maximal force ($F_0$) and velocity ($V_0$) estimations obtained from the FV profile.

*Altitude effects*

4) **Chapter 3.4**. To explore the influence of moderate altitude on ballistic performance and EMG activation during a lower-body resistance training session comprising different (heavy vs. light) external loading conditions. It was hypothesized that greater performance decrements throughout the session would be observed at moderate altitude, specially during the heavy load condition.

5) **Chapter 3.5**. To explore the effects of a power-oriented IHRT intervention performed at moderate altitude on the functional (i.e. maximal and explosive measures of muscle

strength), neuromuscular (i.e. voluntary EMG activation) and morphological (i.e. muscle architecture) responses. It was hypothesised that resistance training at moderate altitude would lead to greater adaptations in muscle strength, neuromuscular and morphological responses.

**Table 2.1:** Characteristics of the different studies carried out in the present Doctoral Thesis.

| Study | Title | Design | Participants | N | Gender | Methods | Statistical methods |
|---|---|---|---|---|---|---|---|
| Study 1 | Influence of a cluster set configuration on the adaptations to short-term power training | Chronic | Recreational athletes | 19 | males | Force plate, linear encoder | ANOVA, magnitude-based inferences |
| Study 2 | Muscle activation during power-oriented resistance training: continuous vs. cluster set configurations | Acute | Recreational athletes | 18 | males | Force plate, linear encoder, EMG | ANOVA |
| Study 3 | Associations of the force-velocity profile with isometric strength and neuromuscular factors | Crossectional | Recreational athletes | 43 | males and females | Force plate, strain gauge, EMG, US | Multiple linear regression |
| Study 4 | Acute effects of moderate altitude on performance and lower-body muscle activation during resistance training | Acute | Moderately resistance trained | 22 | males | Force plate, linear encoder, EMG | ANOVA |
| Study 5 | Intermittent resistance training at moderate altitude: effects on the force-velocity relationship, isometric strength and muscle architecture | Chronic | Recreational athletes | 24 | males | Force plate, strain gauge, EMG, US | ANOVA, magnitude-based inferences |

# Chapter 3

# Methods, Results and Discussion.

## 3.1 Study 1: Influence of a cluster set configuration on the adaptations to short-term power training

### 3.1.1 Methods

#### Overview

A randomized repeated measures design was employed to evaluate the effects of set configuration during loaded countermovement jump (CMJ) training on maximal force, velocity and power output at different loading conditions. Measurements of vertical ground reaction force (GRF) during loaded CMJ and maximal dynamic strength (1RM) in the half squat exercise were performed. Prior to the power training intervention, subjects took part of a sequential training approach aiming to increase strength levels (Cormie, Mcguigan, and Newton 2010; Zamparo, Minetti, and di Prampero 2002). Specifically, subjects performed 8 weeks of progressive intensity strength training including two weeks of strength circuit training, three weeks of hypertrophy-oriented strength training and three weeks of maximal strength training. Training exercises, volumes and intensities are shown in Figure 3.1. Subjects were then randomly allocated to a "traditional" (TT) or a "cluster" (CT) power training group. CMJ performance at three different external loads relative to their body weight (BW) (25%, 50% and 75% BW), and maximal strength levels (1RM) of the lower limbs were assessed four times (T1, T2, T3 and T4) across the 11-week resistance training intervention.

## Participants

Nineteen active male volunteered to participate in this study. Body weight, height and age at the start of the study were 76.6 ± 9.7 kg, 178.3 ± 6.3 cm and 23.6 ± 5.8 years, respectively. The study was approved by the university's Ethical Advisory Committee and all subjects signed an informed consent in accordance with the Declaration of Helsinki.

## Testing procedures

### Testing protocol

All testing sessions were performed between 11h and 20h, at least 72h after the last training session. Each subject was always tested at a consisted time of day (± 1h). Subject's weight (Tanita BF 350, Tokyo, Japan) and height (Seca Instruments Ltd., Hamburg, Germany) were measured at the start of each testing session. Subjects performed a standardized warm-up protocol consisting of 5 min cycling, joint mobility exercises and 3-4 unloaded CMJ repetitions. Afterwards, they completed an incremental loading CMJ test (load accuracy $\geq$ 0.25kg) at 25%, 50% and 75% of their own BW in a Smith Machine (Technogym, Gambettola, Italy). Instructions were given to keep constant downward pressure on the barbell and to jump as high as possible. At each load, 2 attempts were performed and rest between both repetitions was set to 1 min. The repetition with the highest take off velocity was selected for further analysis. In order to minimize variation on jump kinematic and kinetic patterns, a manual goniometer and an adjustable rod on a tripod were used to set CMJ depth to 90º knee angle for each subject. Subjects were instructed to squat until touching the rod with their glutei. Additionally, visual biofeedback was provided during each jump using a video camera placed laterally to subjects' position (Figure 3.1). Afterwards, subjects completed a maximal dynamic strength test (1RM) during the half squat exercise (90º knee angle) on the same Smith Machine. Three sets of 3-6 repetitions at increasing loads were completed before performing one set of 2-3 repetitions to failure. Rest periods between sets were kept to 5 min. Squat depth was also standardized as described above and visual feedback from the video camera laterally positioned was also provided. Spotters verbally encouraged subjects throughout all lifts. Using the 2-3RM load, 1RM values were predicted using Brzycki's equation (Brzycki 1993).

### Data processing

All jumps were performed on a force plate (Type 9260AA6, Kistler, Switzerland). Vertical GRF data were recorded at 1000 Hz using an analog-to-digital converter (DAQ system 5691A1, Kistler) and collected through the BioWare software (Kistler, Winterthur, Switzerland). Data analysis was performed using custom written scripts computed with Matlab (Version R2015a, The Mathworks, Natick, Massachusetts, USA). Baselines were carefully checked and a 1-second averaged GRF period was selected as baseline on each jump. The onset of each CMJ was taken when GRF was 10N below the baseline. Force, velocity and power data were calculated from the GRF $\mathrm{F_z}$ component, according to the impulse-momentum approach (Linthorne 2001). Specifically, vertical instantaneous acceleration (a) of the center of mass was first calculated using the following equation (Equation (3.1)):

$$a = \frac{F}{m} - g \tag{3.1}$$

Where $F$ is the force, $m$ is the total body mass (kg) and $g$ is the gravity.

Acceleration was then integrated once to provide instantaneous vertical velocity ($v$) using the following equation (Equation (3.2)):

$$v = \int a \; dt + V_0 \tag{3.2}$$

Given that each CMJ attempt started from static conditions, at $t_0$:

$$v_0 = 0 \tag{3.3}$$

Power (W) was then calculated as the product of force and velocity ($P = F \times v$). Peak force ($F_{25}$, $F_{50}$, $F_{75}$), velocity ($V_{25}$, $V_{50}$, $V_{75}$) and power ($P_{25}$, $P_{50}$, $P_{75}$) data were further analyzed at each loading condition.

### Force-Velocity profiling

For each participant, the force-velocity relationship obtained from the peak force and velocity values, was modeled by a least-squares linear regression. The intercepts of the F-v curve with the force and velocity axis were taken to obtain the theoretical maximal force ($F_0$) and maximal velocity ($V_0$). The slope of the F-v relationship and maximal theoretical power output ($P_0$, computed as $P_0 = (F_0 \times V_0)/4$) (Samozino et al. 2012) were also obtained for each participant.

### Training program

Throughout the course of the intervention, subjects refrained from any additional lower body strength training activity. Subjects attendance to training sessions was 100% and all sessions were supervised. An overview of the training intervention is illustrated in Figure 3.1. Training sessions started with a standardized warm-up protocol consisting of 5 min cycling, 3-5 min of lower-body mobility exercises, 10 back squat repetitions with an unloaded 17 kg barbell and 6 back squat repetitions with a load corresponding to 50% of the correspondent session training intensity. During the 3-week power training period, five unloaded CMJs and five CMJs with a 17 kg barbell were added to the warm-up protocol. Training intensity was adjusted on each training phase relative to the latest 1RM assessment.

All training sessions were completed twice weekly with at least 48h rest between them. During the power training period, subjects on both TT and CT groups were provided with velocity feedback from a linear transducer (Globus Italia, 1000Hz). Specifically, peak velocity for each repetition was screened as a graph bar and verbal encouragement was given to achieve maximal peak velocity.

### Statistical Analysis

Both clinical magnitude-based inferences (Batterham and Hopkins 2006) and the null-hypothesis significance testing were performed to assess changes in the dependent variables. Data is presented as mean ± standard deviation (SD). For presentation purposes, data within figures are mean ± standard error of the mean (SEM). The normality of the data was tested using a Shapiro-Wilk's test. Between-group differences at baseline were tested using independent samples Student's t-tests. Paired Student's t-tests were employed to assess changes on peak power after the hypertrophy and maximal strength training periods. A two-way repeated measures ANOVA was used to evaluate the influence of group (CT *vs.* TT) and repetition number (1 *vs.* 2 *vs.* 3 *vs.* 4 *vs.* 5 *vs.* 6) on the peak velocity percentage change from first repetition averaged across all power training sessions. Post-hoc tests were performed by means of Bonferroni procedures when appropriate. A two-way repeated measures ANOVA was employed to assess the influence of time (pre *vs.* post) and group (TT *vs.* CT) on each dependent variable. The level of significance was set at $p < 0.05$. Cohen's d effect sizes (ES) (90% CI) and thresholds [$< 0.5$ (*small*); 0.5-0.79 (*moderate*); $\geq 0.8$ (*large*)] were also used to compare the magnitude of the differences. The smallest worthwhile change in the mean in standardized (Cohen) units was set to 0.2 of the between-subjects standard deviation. Quantitative chances of better or worse effects (i.e. greater than the smallest worthwhile change) were assessed qualitatively as follows: <1%, *almost certainly not*; 1-5%, *very unlikely*; 5-25%, *unlikely*; 25-75%, *possible*; 75-95%, *likely*; 95-99%, *very likely*; and >99%, *almost certain.* If the chances of having beneficial or detrimental were both >10%, the true difference was assessed as unclear. Magnitude based inferential statistics were calculated using a modified built-in spreadsheet.

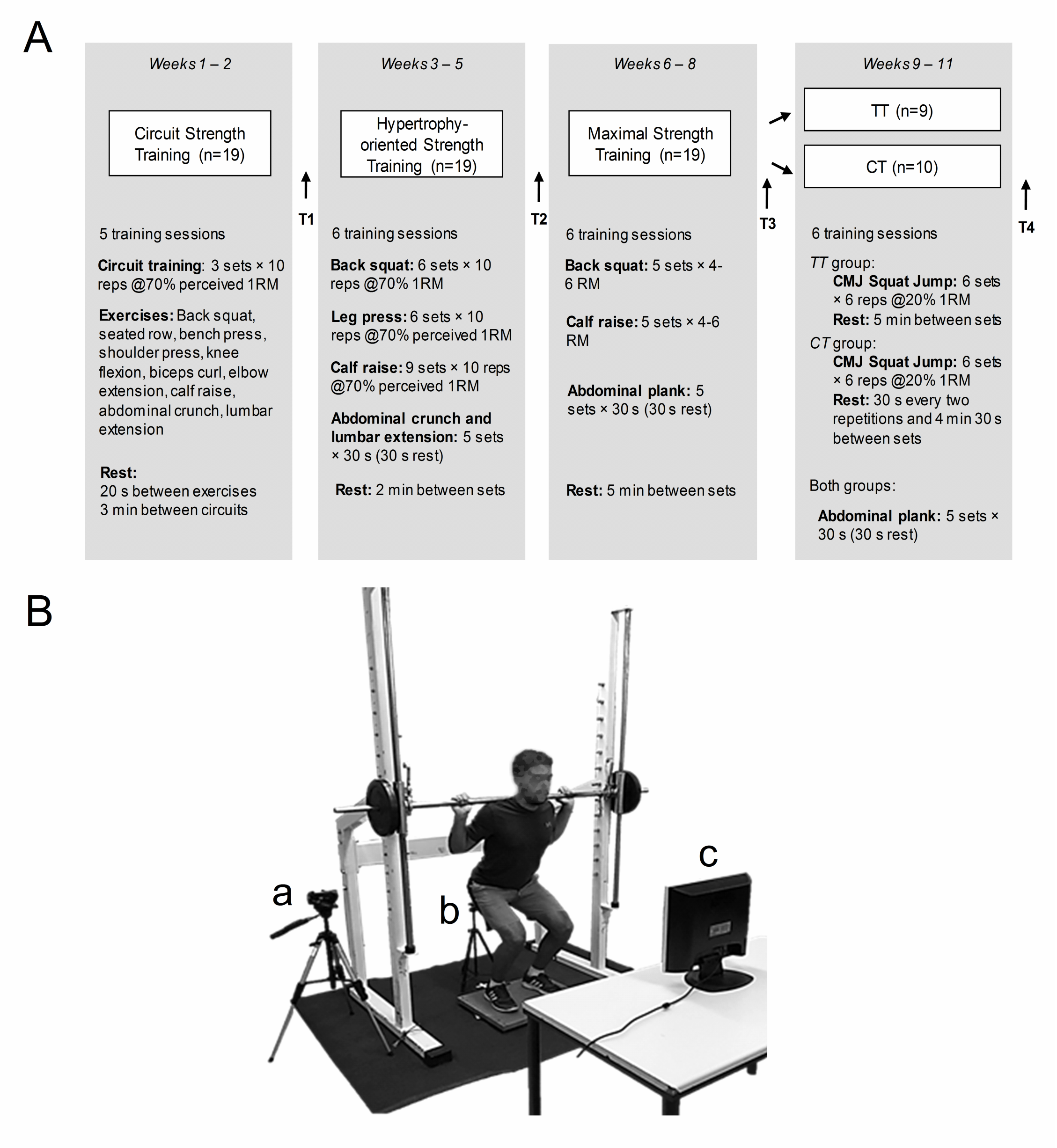

**Figure 3.1:** Training program and experimental set up. A) Exercises, sets, repetitions (reps) and intensities (% 1RM) prescribed in the entire resistance training intervention. Training sessions were performed twice weekly. B) Experimental set up including video-camera (a), screen (c) and adjustable rod on a tripod (b) used to control squat depth.

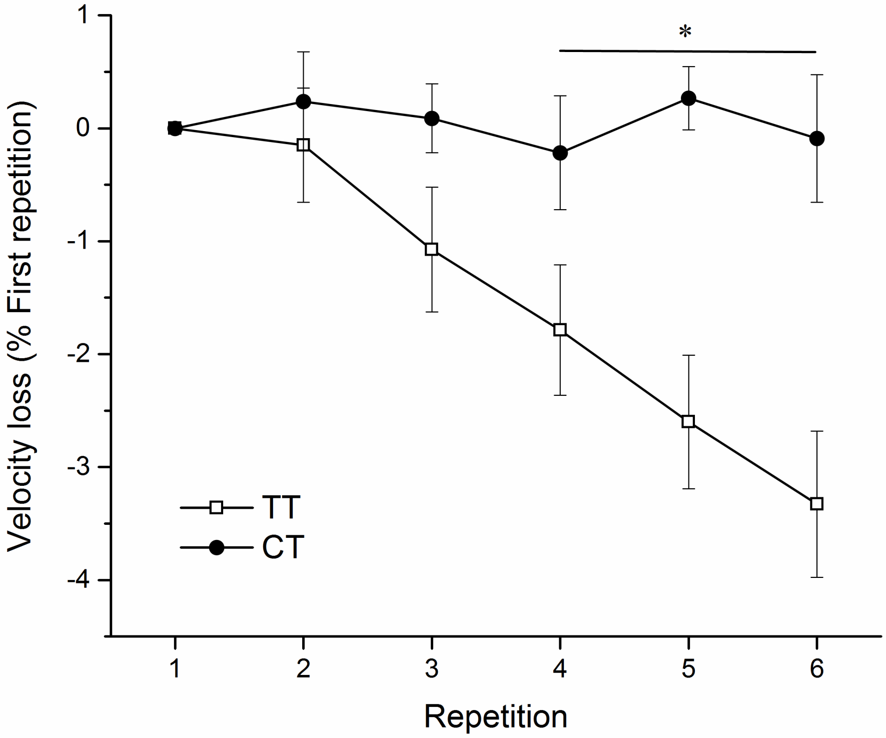

**Figure 3.2:** Velocity loss during the power training sessions. Peak velocity percentage changes from the first repetition. The figure represents all repetitions averaged across the 6 power training sessions from the Traditional (TT) and Cluster training (CT) groups. Data are mean ± SEM. * $p < 0.001$, ES $\geq 0.94$.

### 3.1.2 Results

At the start of the training intervention, there were no differences between groups in BW ($p = 0.574$) and 1RM values ($p = 0.813$). No changes in BW were observed during the training intervention (75.2 ± 9.6 *vs.* 75.6 ± 9.9 kg; $p > 0.05$). The ANOVA showed a large (ES = 1.01) significant condition × repetition interaction effect ($p < 0.001$) due to greater decreases in peak velocity at repetitions 4, 5 and 6 during TT ($p \leq 0.02$; ES $\geq 0.94$; Figure 3.2).

Large improvements in maximal strength levels (1RM) were observed from T1 to T2 (160.3 ± 25.7 *vs.* 182.9 ± 17.7 kg; $p < 0.001$, ES = 1.01) and from T2 to T3 (182.9 ± 17.7 *vs.* 201.3 ± 17.6 kg; $p < 0.001$, ES = 1.06) in all subjects. ANOVA showed no significant main effect of time (201.3 ± 15.5 *vs.* 205.2 ± 20.7 kg; $p = 0.06$, ES = 0.2) or time × group interaction from T3 to T4 (201.7 ± 20.1 *vs.* 206.9 ± 21.8 kg for TT, and 200.9 ± 16.1 *vs.* 203.6 ± 20.7

kg for CT; $p = 0.53$, ES = 0.1).

Changes in $P_{25}$, $P_{50}$ and $P_{75}$ after the 3-wk moderate and the 3-wk maximal strength training periods are shown in Table 3.1 and Table 3.2, respectively.

**Table 3.1:** Effects of the 3-week hypertrophy training period on CMJ peak power at 25%, 50%, and 75% of body weight loads during Test 1 (T1) and Test 2 (T2).

| | T1 $(W \cdot kg^{1})$ | T2 $(W \cdot kg^{1})$ | % change | ES (90% CI) | % chances |
|---|---|---|---|---|---|
| $P_{25}$ | 49.89 ± 5.97 | 53.45 ± 6.28 | +7.31 ± 6.56 | 0.57 (0.37 to 0.77) | 100/0/0 |
| $P_{50}$ | 53.42 ± 7.38 | 55.94 ± 7.42 | +5.10 ± 8.71 | 0.33 (0.09 to 0.56) | 82/18/0 |
| $P_{75}$ | 54.12 ± 9.18 | 55.67 ± 7.84 | +3.87 ± 11.51 | 0.16 (-0.09 to 0.41) | 39/60/1 |

**Table 3.2:** Effects of the 3-week maximal strength training period on CMJ peak power at 25% ($P_{25}$), 50% ($P_{50}$) and 75% ($P_{75}$) of body weight loads during Test 3 (T3) and Test 4 (T4).

| | T2 $(W \cdot kg^{-1})$ | T3 $(W \cdot kg^{-1})$ | % change | ES (90% CI) | % chances |
|---|---|---|---|---|---|
| $P_{25}$ | 53.45 ± 6.28 | 54.30 ± 6.71 | +1.63 ± 4.79 | 0.14 (-0.03 to 0.30) | 25/75/0 |
| $P_{50}$ | 55.94 ± 7.42 | 56.02 ± 8.45 | +0.31 ± 9.92 | 0.01 (-0.27 to 0.29) | 12/78/10 |
| $P_{75}$ | 55.67 ± 7.84 | 55.03 ± 9.54 | -1.08 ± 10.76 | -0.07 (-0.31 to 0.18) | 4/78/18 |

The F-v relationship changes throughout the training intervention including all subjects are presented in Figure 3.3.

A significant main effect for time revealed that 3 weeks of power training incremented $P_{25}$ (54.29 ± 6.71 *vs.* 57.65 ± 7.07 W·kg$^{-1}$, ANOVA, $p < 0.001$, ES = 0.49) and $P_{75}$ (55.03 ± 9.54 *vs.* 57.44 ± 8.74 W·kg$^{-1}$, ANOVA, $p = 0.041$, ES = 0.26) due to *moderate* increments in $V_{25}$ (2.39 ± 0.21 *vs.* 2.53 ± 0.21 m·s-1, ANOVA, $p < 0.001$, ES = 0.67) and *small* increases $V_{75}$ (2.02 ± 0.27 to 2.11 ± 0.25 m·$^{s-1}$, ANOVA, $p = 0.012$, ES = 0.35). Time × group interaction effects (ANOVA) in force, velocity and power are shown in Table 3.3. Individual changes in peak power at each loading condition after both traditional and cluster training are shown in 3.4.

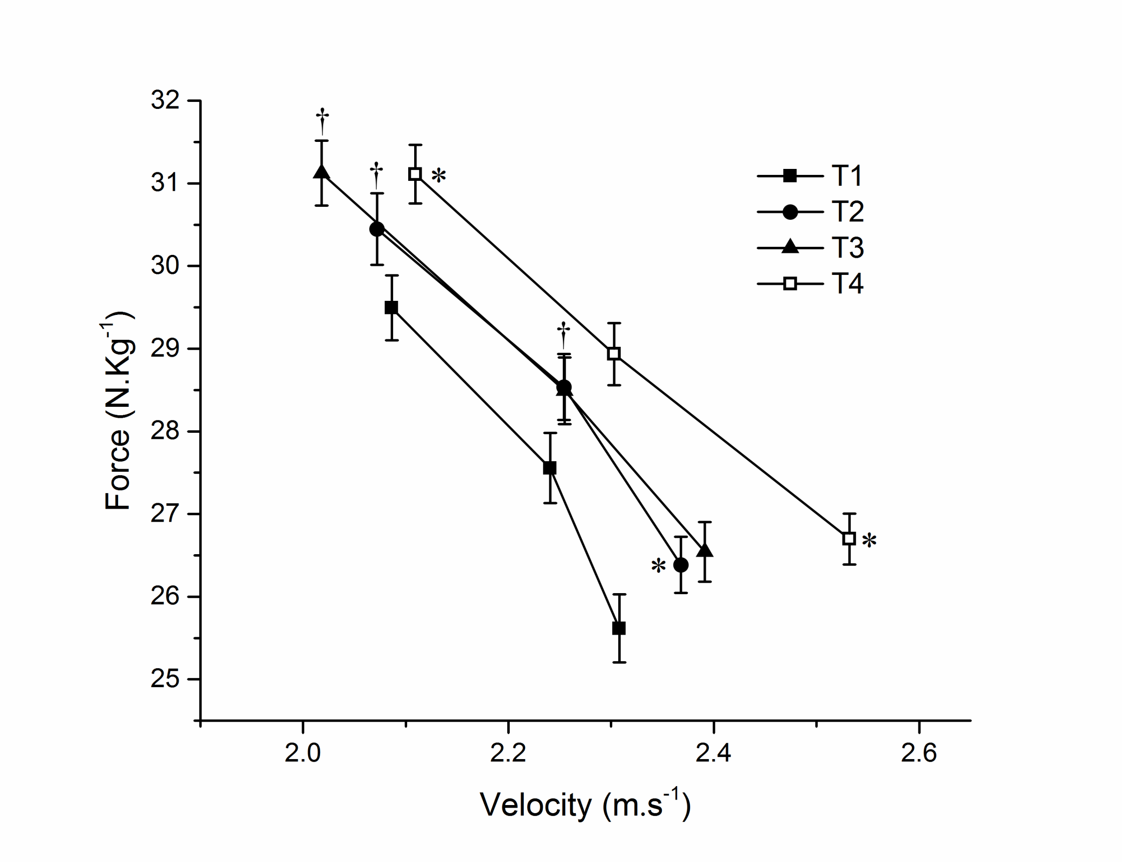

**Figure 3.3:** Force-velocity curves following the introductory mesocycle [2 weeks of circuit weight training (T1)], general strength mesocycle [(3 weeks of hypertrophy-oriented resistance training (T2)], maximal strength mesocycle [3 weeks of maximal resistance training (T3)] and especial strength mesocycle [3 weeks of power oriented resistance training (T4)] (all subjects, n=19). $*$ Significant increase in peak velocity compared with the previous test ($p < 0.05$). † Significant increase in peak force from previous test ($p < 0.05$).

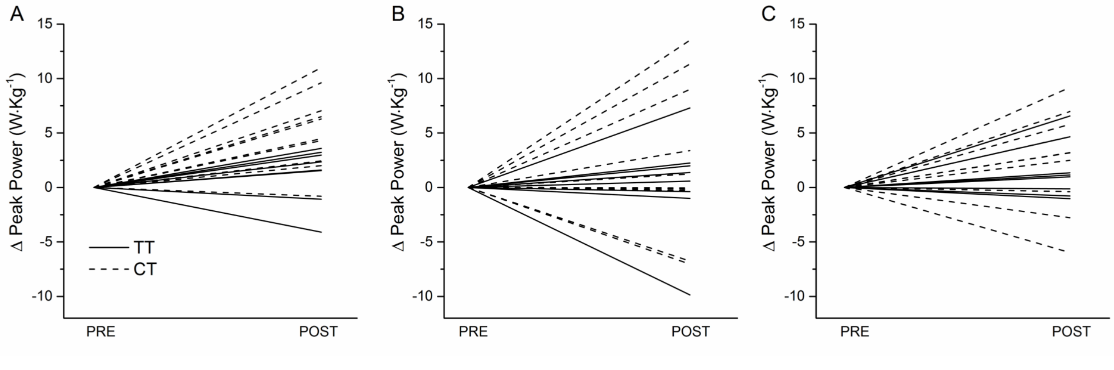

**Figure 3.4:** Individual absolute changes in peak power (W·kg$^{-1}$) at 25% (A), 50% (B) and 75% (C) body weight (BW) loading conditions after 3 weeks of traditional (TT, solid lines) and cluster (CT, dashed lines) resistance training.

**Table 3.3:** Pre to post changes in power, velocity and force at each loading condition after the 3-week cluster (CT) *vs.* traditional (TT) power training

|  |  |  | Between-group differences |  |  |
|---|---|---|---|---|---|
|  | TT group (T4 - T3 $\Delta; W \cdot kg^{-1}$) | CT group (T4 - T3 $\Delta; W \cdot kg^{-1}$) | ES (90% CI) | % chances | Interaction Effects (P, ANOVA) |
| $P_{25}$ | +1.21 ± 2.45 | +5.29 ± 3.57 | 0.55 (0.22 to 0.88) | 96/4/0 | 0.011 |
| $P_{50}$ | +0.27 ± 4.50 | +2.42 ± 7.01 | 0.23(-0.27 to 0.74) | 54/38/8 | 0.444 |
| $P_{75}$ | +1.43 ± 2.55 | +3.29 ± 5.91 | 0.18 (-0.17 to 0.53) | 46/51/4 | 0.395 |
| $V_{25}$ | +0.06 ± 0.09 | +0.22 ± 0.10 | 0.71 (0.37 to 1.05) | 99/1/0 | 0.001 |
| $V_{50}$ | +0.01 ± 0.17 | +0.08 ± 0.24 | 0.24 (-0.35 to 0.84) | 55/34/11 | 0.494 |
| $V_{75}$ | +0.06 ± 0.09 | +0.12 ± 0.17 | 0.22 (-0.14 to 0.58) | 53/44/3 | 0.305 |
| $F_{25}$ | +0.43 ± 0.96 | -0.09 ± 1.73 | -0.30 (-0.95 to 0.34) | 9/30/61 | 0.616 |
| $F_{50}$ | +0.71 ± 0.84 | 0.21 ± 1.27 | -0.26 (-0.70 to 0.19) | 5/36/59 | 0.333 |
| $F_{75}$ | +0.18 ± 0.62 | -0.18 ± 1.09 | -0.19 (-0.55 to 0.18) | 4/47/49 | 0.394 |

ANOVA denoted no significant main effects of time for $F_0$ (49.92 ± 12.37 *vs.* 50.45 6 15.05 N·kg$^{-1}$; $p = 0.34$; ES = 0.05), $V_0$ (5.61 ± 1.26 *vs.* 6.00 ± 1.47 m·s$^{-1}$; $p = 0.14$, ES = 0.41) or Slope (29.66 ± 4.64 *vs.* 29.59 ± 6.36; $p = 0.95$, ES = -0.01). There was a significant main effect of time for $P_0$ (67.75 ± 10.11 *vs.* 71.80 ± 2.11 W·kg$^{-1}$; $p = 0.005$, ES = 0.55). No significant time × group interaction effects were found in any of the F-v profile variables (Table 3.4).

**Table 3.4:** Pre to post changes in the F-v derived parameters after the Traditional and Cluster training.

| | Traditional Training | | Cluster Training | | Between-group differences | | |
|---|---|---|---|---|---|---|---|
| | T3 | T4 | T3 | T4 | ES (90% CI) | % chances | P value |
| $F_0(N \cdot kg_{-1})$ | 47.97 ± 10.44 | 50.59 ± 19.19 | 51.87 ± 14.3 | 50.33 ± 9.22 | -0.31 (-1.17 to 0.56) | 16/26/58 | 0.537 |
| $V_0(m \cdot s_{-1})$ | 5.51 ± 1.23 | 5.94 ± 1.60 | 5.73 ± 1.30 | 6.08 ± 1.34 | -0.06 (-0.73 to 0.61) | 25/40/36 | 0.870 |
| $P_0(W \cdot kg_{-1})$ | 63.95 ± 8.89 | 69.61 ± 8.61 | 71.56 ± 11.19 | 73.99 ± 8.28 | -0.27 (-0.65 to 0.10) | 2/34/63 | 0.207 |
| Slope | -9.41 ± 3.99 | -10.09 ± 7.88 | -9.91 ± 5.24 | -9.09 ± 4.34 | 0.29 (-0.66 to 1.25) | 57/24/19 | 0.593 |

### 3.1.3 Discussion

The current study aimed to evaluate the influence of set configuration on the short-term power training adaptations. Accordingly, the effects of a 3-week power training period comprising TT or CT on strength and power output were investigated. Compared to TT, greater improvements in peak power and velocity output were observed after CT. These results seem to support previous suggestions on the efficacy of CT at inducing short-term velocity and power adaptations following ballistic CMJ training.

In agreement with our hypothesis, the CT group showed greater improvements in power output (9.7% *vs.* 2.7% in $P_{25\%}$) and movement velocity (8.2% *vs.* 2.3% in $V_{25\%}$) than the TT group. Furthermore, a tendency towards greater improvements in $V_0$ following CT was observed from the F-v profile (+19.1% *vs.* 7.0%), although subsequent decrements in $F_0$ were also observed after CT compared to TT (-8.8% *vs.* +3.2%, respectively). These results support previous suggestions on the effectiveness of cluster set configurations for explosive ballistic training (Haff et al. 2008). Hansen et al. (2011) also described greater velocity and power adaptations after squat jump CT in elite athletes, although these improvements were not consistent across the loading conditions tested. Similarly, we observed greater power and velocity improvements after CT at low loading conditions, but no meaningful differences were detected at higher loading conditions. Load-specific training adaptations may therefore have been responsible for these results (Cormie, McGuigan, and Newton 2010). The power training load employed in the present study was velocity-oriented (20% 1RM) and performance was consequently maximized mostly at light loading conditions. Additional research should examine whether cluster set configurations are also beneficial at eliciting greater adaptations when training at different loading conditions (i.e. maximal strength or hypertrophy-oriented training).

Consistent with previous studies (García-Ramos et al. 2015; Tufano et al. 2016), the barbell velocity data registered during the power training sessions showed that the inclusion of a 30 s rest every two repetitions effectively maximized training intensity, which may have influenced the mechanisms of adaptation during CT. Interestingly, earlier investigations have shown that cluster set configurations lead to faster phosphocreatine replenishment rates (Gorostiaga et al. 2012), lower acid lactic accumulation (Girman et al. 2014) and lower ratings of perceived exertion (Hardee et al. 2012; Iglesias-Soler, Mayo, et al. 2016). Given that the actual movement velocity (Pareja-Blanco et al. 2014) and the intention to move explosively (Behm and Sale 1993; Iglesias-Soler, Fernández-del-Olmo, et al. 2016) are known to be critical factors when targeting neuromuscular adaptations, CT may have provided optimal conditions for power training adaptations.

Regarding maximal strength gains, no significant changes were observed after the TT or CT periods (+2.5% *vs.* +1.3%, respectively). Training interventions involving continuous set configurations have been proposed to result in greater upper (Lawton et al. 2004; Rooney, Herbert, and Balnave 1994) and lower body maximal strength gains and force application while jumping (Hansen et al. 2011), although this is not always the case (Iglesias-Soler, Mayo, et al. 2016). Given the velocity-oriented training load employed in our intervention, and considering the improvements in 1RM (+21.7%) after the previous 6-week sequential strength training period, no substantial changes in maximal strength levels were expected after the power training period. Notwithstanding, despite no meaningful maximal strength improvements following the power training phase, greater force application during CMJ at 50% BM, and improvements in $F_0$ (+3.2%) after TT compared to CT were observed. These findings further support previous research describing greater increments in force application during CMJ after lower body traditional power training (Hansen et al. 2011).

Our results suggest that a cluster set configuration may allow to achieve superior velocity and power performance adaptations following short-term CMJ training. However, several facts must be considered when interpreting these findings. First, it should be taken into account that although subjects were randomly assigned to a CT or TT group based on their maximal strength levels (i.e. 1 RM) (Cormie, Mcguigan, and Newton 2010), the F-v profile imbalance may also be appropriate to be used for training group allocation, which could yield different training effects of cluster loadings on the F-v profile (Jiménez-Reyes et al. 2017). Second, it should be kept in mind that the study sample consisted of active non–resistance-trained subjects. Adaptations may be influenced by training background and the current results should be applied with caution to strength-trained populations.

## 3.2 Study 2: Muscle activation during power-oriented resistance training: continuous vs. cluster set configurations.

### 3.2.1 Methods

#### Overview

Subjects attended the laboratory on two different days. On day one, a one-repetition maximum test (1RM) on the half-squat exercise was performed. On the second day, each subject took part in a power-oriented resistance training session comprising six sets of loaded countermovement jump (CMJ) repetitions. One group of subjects performed continuous repetitions sets (n = 9) and a second group performed clustered sets (n = 9) of loaded CMJs. Ground reaction force (GRF), barbell velocity and surface EMG of the vastus lateralis (VL), vastus medialis (VM) and rectus femoris (RF) muscles were monitored during all CMJs.

### Participants

Eighteen males volunteered to participate in this study (Table 3.5). All participants took part of the 11-week training intervention described in Section 3.1, which ensured that all of them were familiar with the training procedures. The training intervention implied participants to take part first in a general preparatory phase aiming to increase strength levels, followed by a three-week power oriented resistance training (see Figure 3.1). The nature, aims and risks of the experimental procedures were explained to all subjects. The study was approved by the university's Ethical Advisory Committee and all subjects provided informed consent in accordance with the Declaration of Helsinki.

**Table 3.5:** Descriptive data of the participants physical characteristics.

| | Cluster group | Continuous group |
|---|---|---|
| Age (years) | 22.1 ± 2.4 | 25.7 ± 7.6 |
| Body mass (kg) | 74.2 ± 8.4 | 77.3 ± 11.7 |
| Height (cm) | 179.1 ± 6.4 | 177.7 ± 6.5 |
| Half Squat 1RM (kg) | 203.6 ± 20.7 | 206.9 ± 21.8 |
| Half Squat 1RM ($kg^{-1} \cdot kg^{-1}$) | 2.76 ± 0.31 | 2.72 ± 0.41 |

### Testing procedures

### Prediction of one-repetition maximum (1RM)

Subjects completed a 1RM assessment during the half-squat exercise (90º knee angle) using a guided Smith Machine. Three sets of 3-6 repetitions at increasing loads were completed before performing one set of 2-3 repetitions to failure. Resting periods between sets were kept to 5 min. For each subject, squat depth was standardized using a manual goniometer and an adjustable rod on a tripod to set depth to 90 knee angle degrees. Subjects were instructed to squat until touching the rod with their glutei. Using the 2-3RM load, 1RM values were predicted using Brzycki's equation (Brzycki 1993).

### Testing sessions

Before each session, subjects completed a standardized warm-up protocol comprising 5 min jogging, joint mobility exercises, five unloaded CMJs and five CMJs with 50% of the corresponding training load. Next, subjects completed a power training protocol consisting of either continuous (6 sets of 6 repetitions, 5 min rests between sets) or clustered sets (6 sets of 6 repetitions with 30 s rests every two repetitions and 4 min rests between sets) at 20% 1RM. Subjects were instructed to keep constant downward pressure on the barbell and to jump as high as possible. In order to minimize variation in jump kinematic and kinetic patterns (Mandic, Jakovljevic, and Jaric 2015), CMJ depth was controlled using an adjustable rod on a tripod as described in the previous section.

### Data processing

Data analysis was performed using custom-written scripts computed with MATLAB (version R2015a; The Mathworks, Natick, Massachusetts, USA).

### Power output

Ground reaction force (GRF) was recorded and sampled at 1kHz using a force plate (Type 9260AA6, Kistler, Switzerland). A 3rd order Butterworth analog anti-aliasing-filter (500 Hz cut-off frequency) was automatically applied during online signal recording (DAQ System Type 5695B, Kistler, Switzerland). The system centre of mass (COM) velocity was calculated from Fz GRF and used to identify the concentric part of the movement. Precisely, net GRF was first calculated by subtracting the system weight and then divided by the system mass to provide acceleration. Thereafter, acceleration was numerically integrated to provide instantaneous COM velocity. The concentric movement phase was defined from the onset of upward motion (i.e. instantaneous COM velocity > 0 m·s$^{-1}$) to the take-off instant (i.e. GRF < 5 N).

### Electromyography

During all CMJs, EMG activity was wirelessly recorded from the vastus medialis (VM), vastus lateralis (VL) and rectus femoris (RF) muscles (Delsys, Boston, Massachusetts, USA). Raw EMG signals were amplified (× 1000) and sampled at 2 kHz. After skin preparation (shaving, light abrasion and cleaning with alcohol), EMG surface electrodes (Trigno Sensor; Delsys Boston, Massachusetts, USA) were placed according to the surface EMG for non-invasive assessment of muscle recommendations (SENIAM) (Hermens et al. 2000). The electrodes were firmly taped to the skin to minimize movement artifacts during jumps.

Triaxial accelerometry built-in within the EMG sensors (Trigno Sensor; Delsys Boston, Massachusetts, USA) was used to synchronize EMG and GRF signals during offline signal processing. Accordingly, an EMG sensor was firmly attached to the Smith Machine barbell and used to acquire accelerometry data synchronized with the EMG (Figure 3.5). The triaxial accelerometry signals provided by the barbell-attached EMG sensor were pre-processed and time-aligned with the force platform GRF acceleration signals. First, these data were combined into a one-dimensional signal representing the acceleration along the Z axis by applying an optimal rotation matrix obtained by Singular Value Decomposition (Deprettere 1989). The resulting signal was then upsampled to 1 KHz and aligned with the force platform derived COM acceleration by means of a cross-correlation analysis. During this analysis, the time difference (lag) between both signals was obtained as the sample index $i$ that maximizes the cross-correlation function defined as (Equation (3.4)):

$$R_{xy}(l) = \sum_{n=1}^{N-1} a_{EMG}\ (n)\ a_{GRF}(n-l); 0 \leq\ l < N \tag{3.4}$$

where $a_{GRF}\ (n)$ and $a_{EMG}\ (n)$ are the acceleration signals derived from the force platform and the EMG sensor (Z axis combined acceleration), respectively, and $N$ denotes the number of samples of these signals. Once aligned, EMG signals were analyzed on the concentric phase

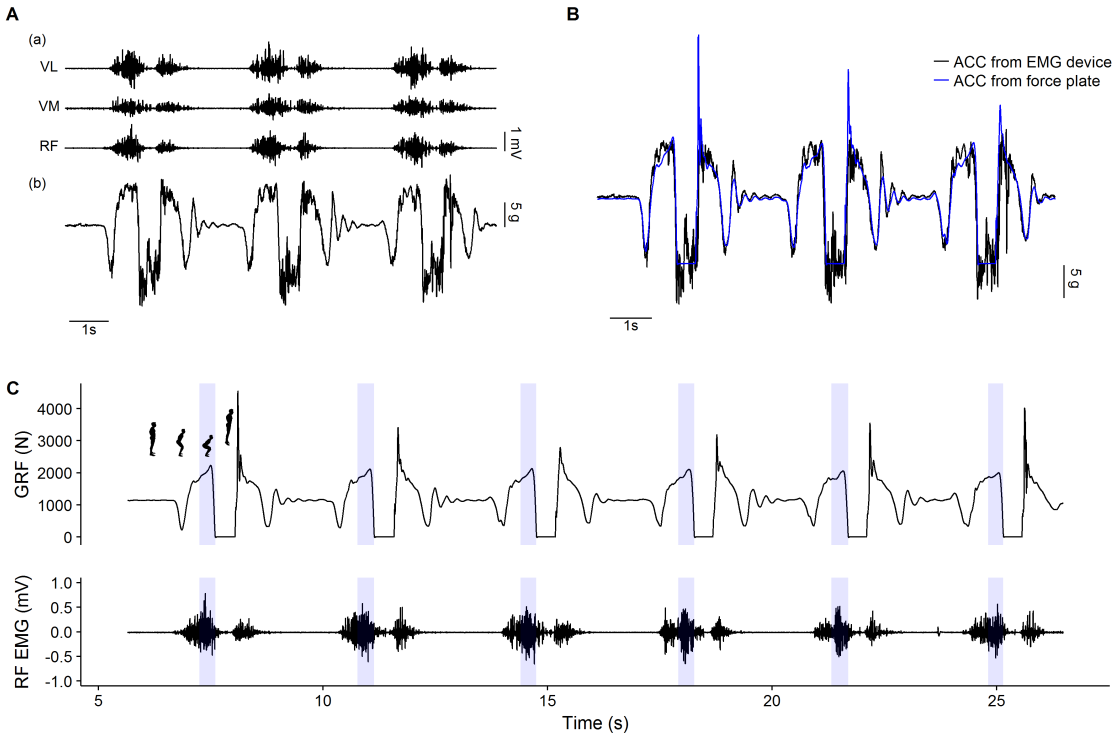

**Figure 3.5:** Typical example of electromyography (EMG), acceleration (ACC) and ground reaction force (GRF) signals recorded during a continuous set of countermovement jumps (CMJ). (A) EMG raw signals from VL, VM and RF muscles (a) synchronously recorded with barbell ACC (b) obtained from a triaxial accelerometer sensor with the same EMG device. (B) Synchronised ACC signals obtained from both, the force plate and EMG devices. (C) Synchronized GRF and raw RF EMG signal during a set of continuous countermovement jumps. Blue rectangles indicate the concentric phase of each CMJ repetition.

of the CMJ. An example of the resulting aligned acceleration signals is shown in Figure 3.5.

EMG signals were first band-pass-filtered (10-400 Hz, 6th order Butterworth filter) for smoothing purposes and to remove any DC offset. Then, the root mean square (RMS), defined in the time domain as (Equation (3.5)):

$$\sqrt{\frac{1}{m} \sum_{m=0}^{M-1} EMG(m)} \tag{3.5}$$

was calculated over the concentric phase of each CMJ repetition (i.e., $m = 0, \ldots, M-1$), where EMG is the filtered EMG signal for each corresponding muscle (i.e. VL, VM, RF). An analysis in the frequency domain was considered by means of the numerical computation of median frequency ($\mathrm{F}_{\mathrm{med}}$), defined as (Equation (3.6)):

$$\int_{f1}^{F_{med}} PS(f) \ \cdot \ df = \int_{F_{med}}^{f_2} PS(f) \ \cdot \ df \tag{3.6}$$

where $PS(f)$ is the EMG signal power spectrum obtained through the MATLAB built-in FFT function, $f_1 = 10Hz$ and $f_2 = 400Hz$. Additionally, the spectral parameter proposed by Dimitrov et al. (2006), $\mathrm{FI_{nsmk}}$, was calculated as (Equation (3.7)):

$$FI_{nsmk} = \frac{\int_{f_1}^{f_2} f^{-1} \ \cdot \ PS(f) \ \cdot \ df}{\int_{f_1}^{f_2} f^{k} \ \cdot \ PS(f) \ \cdot \ df} \tag{3.7}$$

where $k$ is the order of the spectral moment (2, 3, 4 or 5), $PS(f)$ denotes the EMG power-frequency spectrum as a function of frequency $f$, and $f_1$ and $f_2$ were the high- and low-pass frequencies of the amplifier filter (i.e. 10 Hz and 400 Hz), respectively. The changes in values of each EMG parameter (RMS, $\mathrm{F_{med}}$, $\mathrm{FI_{nsm2}}$, $\mathrm{FI_{nsm3}}$, $\mathrm{FI_{nsm4}}$, $\mathrm{FI_{nsm5}}$) were normalized with the first repetition of each set.

**Statistical analyses**

All statistical analyses were performed using R software (version 3.3.2, The R Foundation for Statistical Computing, 2016). Normal distributions of the data were confirmed using a Shapiro-Wilk test. A one-way analysis of variance (ANOVA) was used to compare 1RM values between groups. A two-factor mixed ANOVA was performed to evaluate the effects of repetition (within-subjects factor: 1 *vs.* 2 *vs.* 3 *vs.* 4 *vs.* 5 *vs.* 6) and set configuration (between-subjects factor: continuous *vs.* cluster) on power output data. A separate three-factor mixed ANOVA was applied to each EMG dependent variable (RMS, $\mathrm{F_{med}}$, $\mathrm{FI_{nsm2}}$, $\mathrm{FI_{nsm3}}$, $\mathrm{FI_{nsm4}}$, $\mathrm{FI_{nsm5}}$) with the repetition (6 levels: from $1^{st}$ to $6^{th}$) and muscle (3 levels: VL, VM, RF) as within-subjects and set configuration (continuous *vs.* cluster) as between-subjects factor. When the sphericity assumption in ANOVAs was violated (Mauchly's test), a Greenhouse-Geisser correction was used. Post-hoc tests were performed by means of Bonferroni procedures when appropriate for multiple comparisons. Alpha was set at 0.05. Generalized Eta-Squared measures of effect size and thresholds (0.02 [*small*], 0.13 [*medium*] and 0.26 [*large*]) were calculated along with ANOVA effects. Cohen's d effect sizes and thresholds (>0.2 [*small*], >0.6 [*moderate*], > 1.2 [*large*] and >2 [*very large*]) were also calculated on all dependent variables to observe the magnitude of the standardized mean differences.

### 3.2.2 Results

No differences between groups were observed in absolute ($F = 0.07$, $p = 0.795$, $\eta^2_G < 0.01$) or relative ($F = 0.10$, $p = 0.753$, $\eta^2_G < 0.01$) 1RM values (Table 3.5).

#### Mechanical variables

ANOVA showed a main effect of repetition on power output ($F = 15.31$, p $< 0.001$, $\eta^2_G = 0.02$) due to decrements across repetitions (2210.5 ± 360.1, 2140.4 ± 355.6, 2162.3 ± 361.9, 2111.3 ± 367.2, 2115.5 ± 359.9, and 2066.2 ± 355.0 W, from the first to the sixth repetition, respectively). A set configuration × repetition interaction effect was observed ($F = 7.27$, $p = 0.001$, $\eta^2_G < 0.01$). Specifically, post-hoc analyses revealed significant power output decrements in repetitions five ($p = 0.021$) and six ($p = 0.016$) during the continuous sets, without meaningful changes during the clustered sets. Percentage changes from repetition one and standardized changes (Cohen's d) are shown in Figure 3.6.

#### Electromyography

There was a main effect of repetition on RMS ($F = 6.15$, $p = 0.003$, $\eta^2_G = 0.08$), due to moderate increments from the 4th repetition (1.2 ± 6.4, 2.6 ± 9.1, 5.4 ± 10.0, 4.5 ± 11.3, and 7.1 ± 13.3 % from repetition 2 to 6, respectively). A set configuration × muscle interaction effect was observed ($F = 3.92$, $p = 0.033$, $\eta^2_G = 0.06$) due to moderate greater RMS increments in VL (6.8 ± 11.3 *vs.* -1.7 ± 5.8%) and RF (9.3 ± 14.2 *vs.* 1.9 ± 6.9%) but not VM (2.0 ± 4.7 *vs.* 2.6 ± 7.3%) during the continuous *vs.* clustered set configuration,

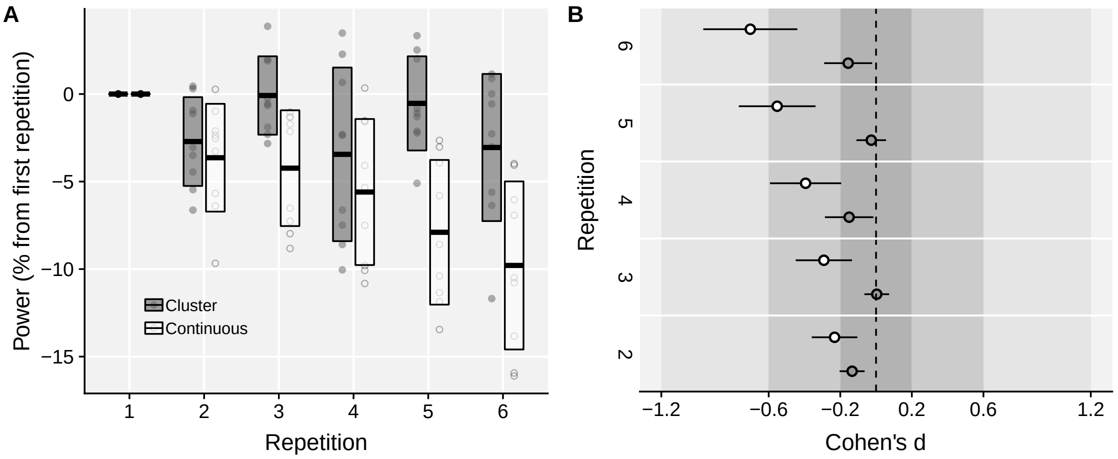

**Figure 3.6:** (A) Power output changes from the 1st repetition during the cluster and continuous set configurations. Horizontal thick lines within bars are mean and upper and lower bars edges are standard deviation. Individual observations are shown as grey or white circles, respectively. (B) Power output standardized mean differences with 90% confidence intervals compared to 1st repetition.

respectively. Furthermore, ANOVA showed a set configuration × repetition interaction effect ($F = 3.11$, $p = 0.046$, $\eta^2_G = 0.04$) due to greater RMS increments during the continuous set configuration (1.8 ± 6.6, 5.8 ± 8.8, 8.2 ± 11.9, 8.9 ± 13.6, and 11.5 ± 15.1%, from repetition 2 to 6, respectively) compared to the clustered sets (0.7 ± 6.3, -0.7 ± 8.3, 2.6 ± 6.9, 0.1 ± 6.1, and 2.6 ± 9.7%, from repetition 2 to 6, respectively). A set configuration × muscle × repetition interaction effect was observed ($F = 1.84$, $p = 0.129$, $\eta^2_G = 0.02$) due to greater RMS increments in VL and RF compared to VM during the continuous set configuration (Figure 3.7).

There was a main effect of repetition on $\mathrm{F}_{\mathrm{med}}$ ($F = 7.67$, $\mathrm{p} < 0.001$, $\eta^2_G = 0.06$) due to significant decrements in the 5th (-4.12 ± 8.55 %; $p = 0.013$) and 6th repetitions (-3.76 ± 8.97%; $p = 0.05$). No meaningful set configuration × repetition ($F = 1.75$, $p = 0.177$, $\eta^2_G = 0.02$), set configuration × muscle ($F = 0.36$, $p = 0.628$, $\eta^2_G < 0.01$) or set configuration × muscle × repetition ($F = 1.46$, $p = 0.205$, $\eta^2_G = 0.02$) interaction effects were observed (Figure 3.8).

Significant main effects of repetition were observed in $\mathrm{FI}_{\mathrm{nsm2}}$ ($F = 23.93$, $\mathrm{p} < 0.001$, $\eta^2_G = 0.27$), $\mathrm{FI}_{\mathrm{nsm3}}$ ($F = 27.96$, $\mathrm{p} < 0.001$, $\eta^2_G = 0.31$), $\mathrm{FI}_{\mathrm{nsm4}}$ ($F = 30.48$, $\mathrm{p} < 0.001$, $\eta^2_G = 0.32$) and $\mathrm{FI}_{\mathrm{nsm5}}$ ($F = 31.57$, $\mathrm{p} < 0.001$, $\eta^2_G = 0.33$) (Figure 3.9). Furthermore, ANOVA showed

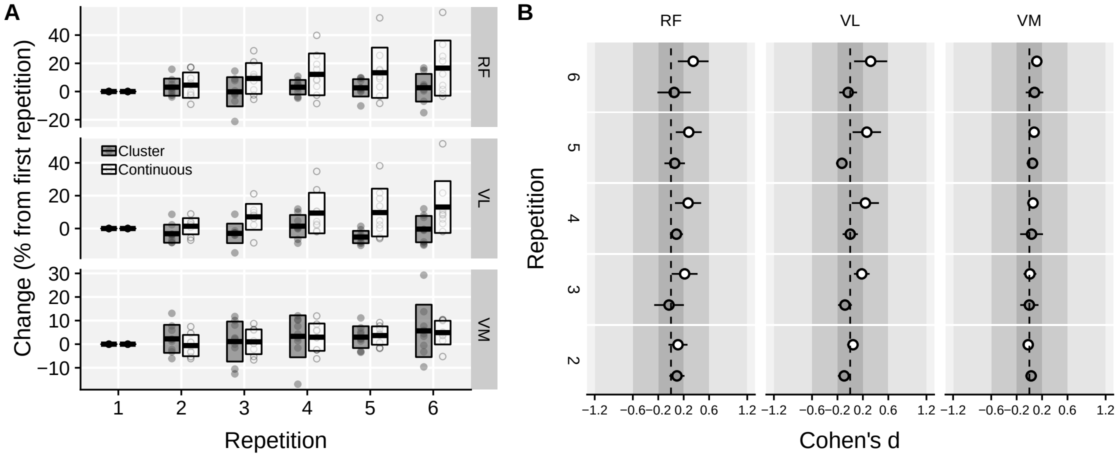

**Figure 3.7:** (A) Percentage changes from the 1st repetition in RMS of VL, VM and RF muscles during both set configurations. (B) RMS standardized mean differences and 90% confidence intervals from 1st repetition for each respective muscle during the cluster (white points) and continuous (grey points) set configurations.

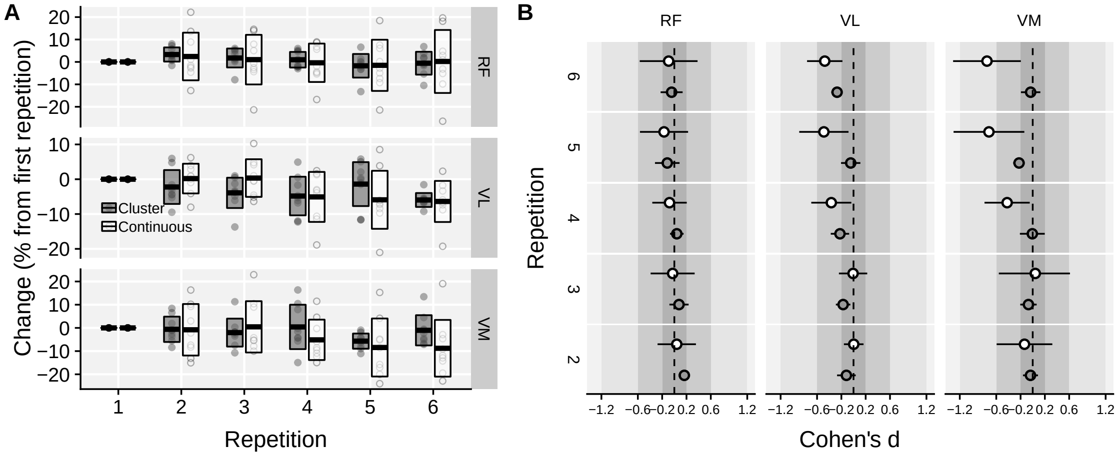

**Figure 3.8:** (A) Percentage changes from the 1st repetition in Fmed during the cluster and continuous configurations for each corresponding muscle. (B) Fmed standardized mean differences and 90% confidence intervals from 1st repetition for each respective muscle during the cluster (white points) and continuous (grey points) set configurations.

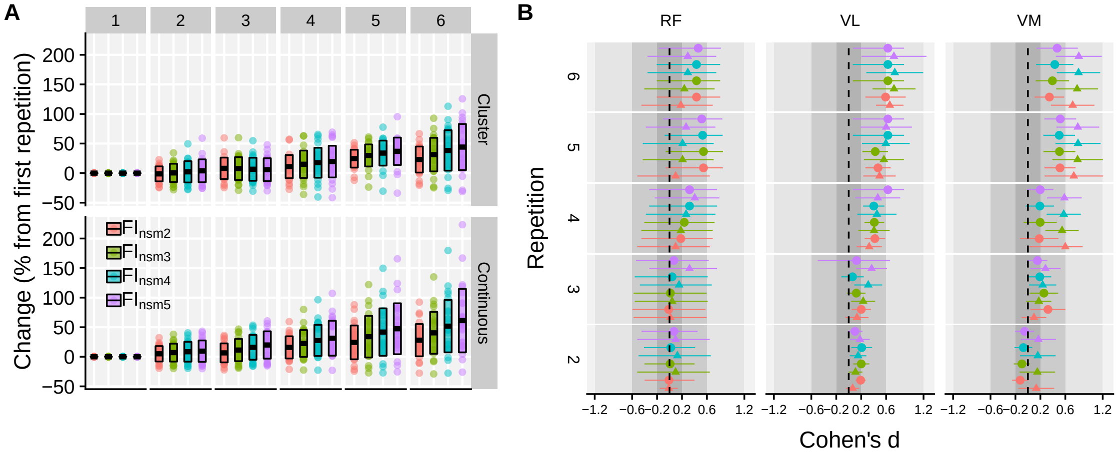

**Figure 3.9:** (A) Percentage changes in $\text{FI}_{\text{nsmk}}$ from the $1^{\text{st}}$ repetition during the cluster and continuous set configurations. (B) Standardized mean differences and 90% confidence intervals from $1^{\text{st}}$ repetition for each respective muscle during the cluster (circles) and continuous (triangles) set configurations. The colour legend shown in panel A also applies in panel B.

significant muscle × repetition interaction effects on $\text{FI}_{\text{nsm2}}$ ($F = 4.53$, $\text{p} < 0.001$, $\eta^2_G = 0.04$), $\text{FI}_{\text{nsm3}}$ ($F = 3.92$, $p = 0.003$, $\eta^2_G = 0.04$), $\text{FI}_{\text{nsm4}}$ ($F = 3.28$, $p = 0.012$, $\eta^2_G = 0.04$) and $\text{FI}_{\text{nsm5}}$ ($F = 2.90$, $p = 0.028$, $\eta^2_G = 0.03$) due to greater progressive increments observed in VM and VL, compared to RF (Figure 3.9). No significant set configuration × repetition or set configuration × repetition × muscle interaction effects were observed.

### 3.2.3 Discussion

The goal of this study was to explore changes in mechanical performance and EMG responses of VL, VM and RF muscles during a typical lower-body power training protocol comprising sets of continuous or clustered repetitions. Accordingly, power output and EMG signal amplitude (i.e. RMS) and frequency analyses (i.e. $\text{F}_{\text{med}}$ and $\text{FI}_{\text{nsmk}}$) were performed during 6 sets of loaded CMJ repetitions. The main results showed greater decrements in power output and increments in RMS of VL and RF muscles during the continuous set configuration. Notwithstanding, despite overall increments in $\text{FI}_{\text{nsmk}}$ and decrements in $\text{F}_{\text{med}}$, no clear differences between set configuration protocols were observed on the explored spectral EMG parameters.

From greater mechanical stress (Tufano et al. 2017) to reduced velocity loss (Oliver et al. 2016), the acute positive effects of clustering repetitions within sets have been linked to reduced fatigue development. Although some research has addressed the metabolic (González-Hernádez et al. 2017) and hormonal implications of cluster set configurations (Girman et al. 2014), scarce neuromuscular evidence is available (Río-Rodríguez, Iglesias-Soler, and Fernández del Olmo 2016). The present results showed greater relative increments in RMS when repetitions were performed continuously, suggesting that the inclusion of 30 s rests every two repetitions minimized muscle fatigue development (i.e. +4.2 *vs.* +10.6 % RMS increase in the 6$^{\text{th}}$ repetition, respectively). While an increase in EMG amplitude seems to be commonly observed during both static (Moritani, Muro, and Nagata 1986) and dynamic fatiguing tasks (Gorostiaga et al. 2012; González-Izal, Rodríguez-Carreño, et al. 2010; Brandon et al. 2015), other studies have found these changes to be load-specific. For instance, maximal strength (i.e. high-load) compared to hypertrophy-oriented (i.e. moderate-load) (Walker et al. 2012) or explosive resistance training protocols (i.e. low to moderate loads lifted at maximal intended velocity) (Linnamo, Häkkinen, and Komi 1997) may result in opposite EMG amplitude changes. Accordingly, it is crucial to carefully consider the specific protocol employed when it comes to interpreting changes in EMG amplitude. Although our study comprised a relatively low load (i.e. 20% 1RM), the observed magnitude of changes in the EMG amplitude is comparable with other investigations using fatiguing protocols (González-Izal, Malanda, et al. 2010). The fact that ballistic maximal velocity intended efforts were performed in the present investigation may imply muscle activation and fatigue patterns specific to the task and contraction mode (Newton et al. 1996). This could partially explain the conflicting evidence in previous research comprising dynamic explosive muscle efforts (Linnamo, Häkkinen, and Komi 1997; Linnamo et al. 2000). The inconsistent findings regarding EMG amplitude variations during repeated efforts encourage caution when it comes to its interpretation, as well as consideration of additional information such as the EMG spectral properties.

In agreement with other studies (González-Izal, Malanda, et al. 2010; Dimitrov et al. 2006), overall decrements in $\mathrm{F_{med}}$ and increments in $\mathrm{FI_{nsmk}}$ were observed during both continuous and clustered training protocols. Notwithstanding, although the changes were of greater magnitude during the continuous repetitions, no meaningful differences between groups were observed. In agreement with Dimitrov et al. (2006), $\mathrm{FI}_{\mathrm{nsmk}}$ progressively augmented as the order of the normalizing spectral moments increased (i.e. $k$, from 2 to 5), while the influence of clustering sets remained trivial. These EMG findings suggest that power training protocols comprising a small number of repetitions (i.e. $< 6$) and long resting periods between sets (i.e. 5 min) are effective to maintain low levels of fatigue, at least in the specific population and loading conditions examined here. Strength trained athletes show greater levels of muscle activation and neural fatigue during training (Ahtiainen and Häkkinen 2009), which could yield greater differences between set configurations. Interestingly, the meaningful effect of cluster sets (i.e. reduced power loss across repetitions) in the absence of clear differences in the EMG spectral parameters highlight the complex nature of muscle fatigue development. Further work is required to establish the potential site-specific muscle fatigue mechanisms (i.e. peripheral *vs.* supraspinal or central) and how these may change with different loadings and set configurations.

The present study showed muscle-specific changes in both RMS and $\mathrm{FI}_{\mathrm{nsmk}}$ parameters, with greater VL and RF changes in the former and VL and VM changes in the latter. Given that most of the available research has reported changes only on VM (Linnamo et al. 2000), RF (Dimitrov et al. 2006) or an average of several muscles (Gorostiaga et al. 2012; Walker et al. 2012; González-Izal, Rodríguez-Carreño, et al. 2010), the current investigation may help to better understand muscle-specific fatigue responses during repeated loaded CMJ repetitions. The greater RMS changes observed in VL are in line with previous research showing a significantly greater contribution of VL during loaded jumping tasks (Giroux et al. 2015). Nevertheless, other factors not addressed in the current investigation may also have contributed to the observed muscle-specific EMG responses. For instance, both synergistic and antagonist muscle activity are known to affect the nervous system ability to activate agonist muscles (Bobbert, Richard Casius, and Kistemaker 2013), notably under fatiguing conditions (Bouillard et al. 2012). It should also be reminded that although inferring mechanistic information from the surface EMG is tempting (Enoka and Duchateau 2015), no accurate interpretation can be made regarding the neuromuscular mechanisms behind the myoelectric symptoms of fatigue reported (Del Vecchio et al. 2017). Both the muscle contractile properties (e.g. sarcolemma excitability, excitation-contraction coupling) and the centrally commanded motor unit activity (i.e. number of active motor units and their discharge rate) are likely responsible for fatigue induced changes in the surface EMG signal. Accordingly, emerging technological advances such as those in high-density surface EMG may help to further understand the underlying neuromuscular mechanisms during real-life resistance training conditions (Del Vecchio et al. 2017).

## 3.3 Study 3: Associations of the force-velocity profile with isometric strength and neuromuscular factors

### 3.3.1 Methods

#### Overview

Participants were first familiarized with all testing procedures on two separate days, without data recording. Thereafter, they visited the laboratory on two separate occasions for official measurements. On day one, muscle architecture, unilateral knee extension isometric force and muscle activation (surface electromyography [EMG]) assessments were performed on the dominant leg. Participants were asked with which leg they preferred to kick a ball to determine limb dominancy (de Ruiter et al. 2010). Specific separate testing protocols were performed to assess maximal and explosive voluntary isometric force. On the second visit to the laboratory (48 h later), participants carried out a progressive loading FV test during the CMJ exercise. All participants were asked to refrain from physical efforts, alcohol intake and maintain their sleep and diet habits 48 h before assessments.

### Participants

Forty-three participants (27 male and 16 female) volunteered to participate in this study. All participants were physically active Sport Science students (age: 22.3 ± 3.2 years; body mass: 68.5 ± 10.4 kg, height: 171.5 ± 8.9 cm) and did not report any physical limitations, health problems or musculoskeletal injuries that could compromise testing. Participants were informed regarding the nature, aims and risks associated with the experimental procedures and informed consent was obtained from all individual participants included in the study. This study was approved by the local ethics committee, and conformed to the standards of the Declaration of Helsinki.

### Testing procedures

### Muscle architecture

B-mode ultrasound images from the quadriceps femoris muscles were obtained by a trained investigator (MyLab25, Esaote Medical Systems, Genova, Italy) using a 12 MHz linear array probe. Specifically, ultrasound images were taken at middle and proximal regions on VM, VL, RF and vastus intermedius (VI) muscles (Figure 3.10). Images were captured at rest while participants were seated in the same custom-made isometric testing chair. Water soluble gel was applied to the probe, allowing minimal pressure on the skin during measurements. The ultrasound probe was orientated parallel to the muscle fascicles and perpendicular to the skin, allowing visualization of aponeuroses and fascicles trajectories on the images.

### Knee extension isometric force

Maximal and explosive voluntary strength assessments were performed on a custom-made isometric rigid dynamometer (Maffiuletti et al. 2016) with knee and hip angles of 110 and 130 degrees (180 = full extension), respectively. Pelvis and shoulders were firmly secured to the chair and a rigid strap was attached to the ankle (2 cm above the lateral malleolus) in series with a calibrated low-noise strain gauge (Force Logic, Swallowfield, UK). The force

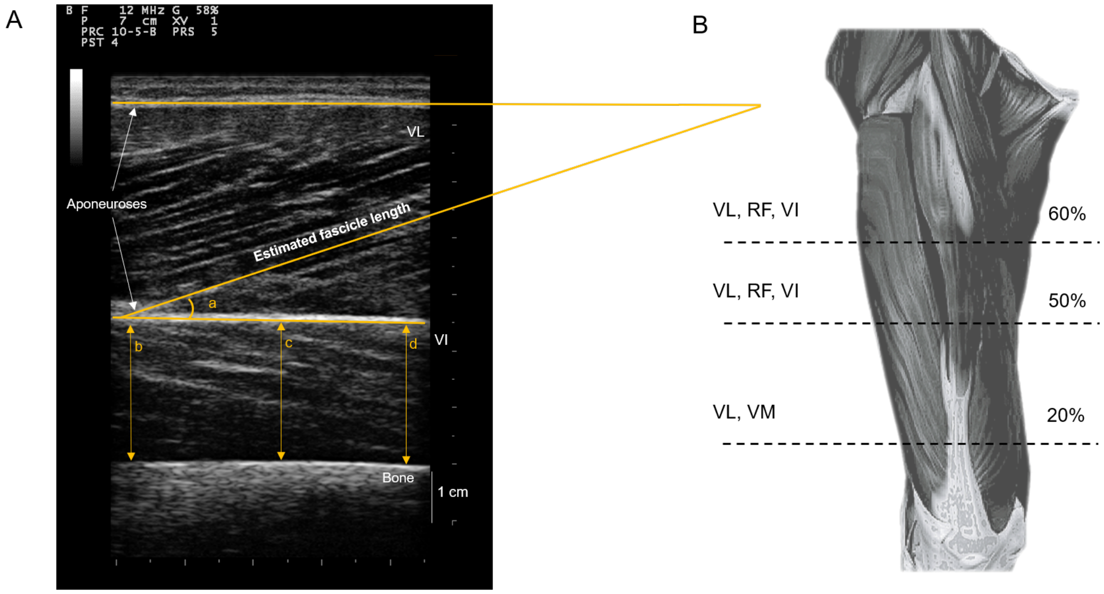

**Figure 3.10:** Muscle structural variables. (A) Muscle thickness measurements were performed in all muscles at three evenly spaced points of the image (b, c, d) and averaged across. Pennation angle measurements were performed on the vastus lateralis muscle, at 20, 50 and 60% of thigh length and averaged. Fascicle length estimations were performed on the vastus lateralis muscle at 50% of thigh length. (B) For each individual muscle, ultrasound images were obtained from three regions relative to thigh length.

signal from the strain gauge was amplified (× 370) and digitized at 1 kHz using a 16-bit analog to digital converter (DT 9804; Data Translation, Marlboro, Massachusetts, USA). Following a standardized warm-up (three sustained contractions for 3-4 s at 20, 40, 60, and 80% of maximum perceived), participants performed three maximal isometric voluntary contractions (MVIC) extending their knee "as hard as possible" for 3-5 s. Resting periods between efforts were set to 1 min. Thereafter, participants performed 10 explosive voluntary contractions interspersed by 30 s resting periods. They were instructed to push "fast, then strong" for ~1 s and to avoid any countermovement or pre-tension prior to the contraction onset (Maffiuletti et al. 2016).

### Surface Electromyography (EMG)

During all isometric force assessments, EMG activity was recorded wirelessly from the vastus medialis (VM), vastus lateralis (VL) and rectus femoris (RF) muscles (Delsys, Boston, Massachusetts, USA). Raw EMG signals were amplified (×1000) and sampled at 2 kHz. After skin preparation (shaving, light abrasion and cleaning with alcohol), EMG surface electrodes

(Trigno Standard Sensor; Delsys Boston, Massachusetts, USA) were placed according to the surface EMG for non-invasive assessment of muscle recommendations (Hermens et al. 2000).

### Countermovement jumps

All jumps were performed on a force plate (Type 9260AA6, Kistler, Switzerland). Vertical ground reaction force (GRF) data were recorded at 1 kHz using an analog-to-digital converter (DAQ system 5691A1, Kistler) and collected through the BioWare software (Kistler, Winterthur, Switzerland). After a standardized warm-up protocol (i.e. 5 min jogging, joint mobility exercises and five unloaded CMJs), participants completed an incremental CMJ test at six absolute loading conditions (male: 0.5, 17, 30, 45, 60 and 75 kg; female: 0.5, 17, 30, 37.5, 45 and 52.5 kg) using a free wood barbell during the 0.5-kg condition and a Smith Machine in the rest of loading conditions (Technogym, Gambettola, Italy). Instructions to keep constant downward pressure on the barbell and to jump as high as possible were given. Jumps were performed with progressive increase in the additional external load and two attempts were performed at each loading condition. Resting time between repetitions and loads was set to 1 and 3 min, respectively.

### Data proccesing

Data analysis was performed using custom written scripts computed with MATLAB (version R2015a; The Mathworks, Natick, Massachusetts, USA). Ultrasound image analysis was done with Image J software (version 1.51J8 National Institutes of Health, Bethesda, USA).

### Muscle architecture

For each quadriceps muscle measurement site, muscle thickness was calculated as the perpendicular distance between superficial and deep aponeuroses, averaged at three evenly spaced points along the image width (i.e. two at the edges, one at midpoint). Thickness measurements from each muscle site were averaged to provide an overall estimation of average quadriceps thickness (Blazevich, Gill, and Zhou 2006). Pennation angle was measured at each measurement site on the VL muscle (i.e. at 20, 50 and 60% of thigh length), as the angle between the deep aponeurosis and the linear arrangement of the muscle fascicle (no curvature was taken into account). Three angle measurements were performed on the two repeated images for each measurement site, and an average was taken to provide overall VL pennation angle. Moreover, fascicle length (FL) estimations were calculated at the mid-section measurement site of the VL muscle (Blazevich et al. 2007) as using the equation (Equation (3.8)):

$$FL = \frac{T}{sin\ \theta} \tag{3.8}$$

where $\theta$ is the fascicle angle and $T$ is the muscle thickness (Blazevich et al. 2003).

### Isometric torque

Force signals recorded from the strain gauge were filtered with a $4^{\text{th}}$ order 150-Hz low pass Butterworth filter and gravity corrected during offline analysis. Torque values were calculated by multiplying force data by the external lever length (distance from the knee joint centre to the centre of the ankle strap). The highest instantaneous peak torque achieved during the MVICs was defined as maximal voluntary torque (MVIC torque). Force signals recorded during the explosive voluntary contractions were first analysed to determine contraction onset and to discard any attempt with pre-tension or countermovement before contraction onset. Force onsets were automatically identified, and visually confirmed (Tillin, Pain, and Folland 2013b), as the last zero-crossing point on the first derivative of the filtered signal force (de Ruiter et al. 2007). To discard any contraction with pre-tension or countermovement, 100 ms baseline force signals prior to contraction onset were fitted with a least-squares linear regression, and absolute slope values greater than 1.5 $N \cdot m \cdot s^{-1}$ were set as a criteria for contraction omission due to potential effects of co-contraction or countermovement on explosive performance (de Ruiter et al. 2007). Explosive contractions reaching peak force $<$ 75% MVIC torque were also discarded. From the remaining explosive voluntary contractions, the three attempts with the highest torque at 100 ms were further analysed and eventually averaged across. For each contraction, torque at 50 ($T_{50}$), 100 ($T_{100}$), 150 ($T_{150}$) and 200 ms ($T_{200}$) after the onset were analysed and used to provide sequential RTD (i.e. $RTD_{0\text{-}50}$, $RTD_{50\text{-}100}$, $RTD_{100\text{-}150}$, $RTD_{150\text{-}200}$). Torque values relative to MVIC torque were also used for further analysis.

## EMG signal processing

EMG signals were first filtered with a 4th order band-pass Butterworth filter (6-450 Hz). For each muscle, the EMG signal during MVICs was assessed with a 500 ms root mean square (RMS) epoch, 250 ms either side of the peak EMG (Buckthorpe et al. 2012). Quadriceps maximal voluntary activation was estimated by averaging across muscles ($EMG_{MVIC}$). During explosive contractions, EMG onset was manually identified as the first muscle to be activated. Specifically, raw EMG signals were graphically displayed with systematic x and y-axis (i.e. 300 ms and ± 0.05 mV, respectively) before visually selecting the last point at which the signal deflected away from baseline (Balshaw et al. 2016). Thereafter, for each muscle, RMS EMG was averaged over four time periods from the EMG onset: 0-50, 50-100, 100-150 and 150-200 ms and normalised to $RMS_{MVIC}$. Further analyses were performed on both, individual (VL, VM, RF) and an average of all three muscles ($EMG_{0\text{-}50}$, $EMG_{50\text{-}100}$, $EMG_{100\text{-}150}$, $EMG_{150\text{-}200}$, respectively).

## Force-velocity relationship

The system centre of mass (COM) velocity was calculated from vertical GRF recordings during jumps. Specifically, net GRF was calculated by subtracting the system weight and then divided by the system mass (kg) to provide acceleration. Acceleration was numerically integrated to provide instantaneous COM velocity. Further analyses were performed on the concentric movement phase, defined from the onset of upward motion (i.e. instantaneous COM velocity $> 0$ m·s$^{1}$) to the take-off instant (i.e. GRF $< 5$ N). Only the repetition with the highest mean velocity was selected for further analysis. At each loading condition, force and velocity were averaged across the concentric phase and modelled by a least-squares linear regression model. The intercepts of the FV linear relationship with the force and velocity axes were taken to calculate $F_0$ (i.e. force at zero velocity) and $V_0$ (i.e. velocity at zero force), respectively. The slope of the relationship was calculated as $\frac{F_0}{V_0}$. Given the linear FV relationship and subsequent parabolic power-velocity and power-force relationships (Jaric 2015), the maximal theoretical power ($P_{max}$ ) was calculated as (Equation (3.9)):

$$P_{max} = \frac{(F_0 \ \times \ V_0)}{4} \tag{3.9}$$

### Statistical Analysis

Descriptive statistics are presented as mean ± standard deviation (SD). As a measure of data dispersion, between-participant coefficients of variation are presented in tables and individual observations depicted in figures. Data normal distribution was confirmed through the Shapiro-Wilk test. Pearson's correlation coefficients were computed to assess bivariate relationships between FV profile related variables (i.e. $F_0$ , $V_0$ , $P_{max}$ and slope), isometric torque performance (MVIC torque, $T_{50}$, $T_{100}$, $T_{150}$, $T_{200}$ [both absolute and relative to MVIC], $RTD_{50\text{-}100}$, $RTD_{100\text{-}150}$, $RTD_{150\text{-}200}$), muscle voluntary neural activation ($EMG_{MVIC}$, $EMG_{0\text{-}50}$, $EMG_{50\text{-}100}$, $EMG_{100\text{-}150}$, $EMG_{150\text{-}200}$) and muscle architecture (quadriceps thickness, VL pennation angle and fascicle length) variables. Pearson's r coefficients were qualitatively interpreted according to the following thresholds: 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*. When large associations between $F_0$ or $V_0$ and any of the isometric torque or neuromuscular variables were observed (Pearson's r coefficient $> 0.7$), predictions were estimated through multiple linear regression models using a manual stepwise approach. When appropriate, Akaike's Information Criterion (AIC) (Arnold 2010), residual standard errors (RSE) and coefficient of determination ($R^2$) were used to assess prediction models. A one-way ANOVA was used to evaluate the effect of gender on EMG quadriceps activation. A two-factor mixed ANOVA was used to evaluate the effect of contraction timing (within-participant factor: $EMG_{0\text{-}50}$, $EMG_{50\text{-}100}$, $EMG_{100\text{-}150}$, $EMG_{150\text{-}200}$), gender (male, female) and muscle (VL, VM, RF) on the normalised EMG activation during the explosive contractions. Statistical significance was set at $p < 0.05$ and 95% confidence intervals were provided when appropriate (95% CI).

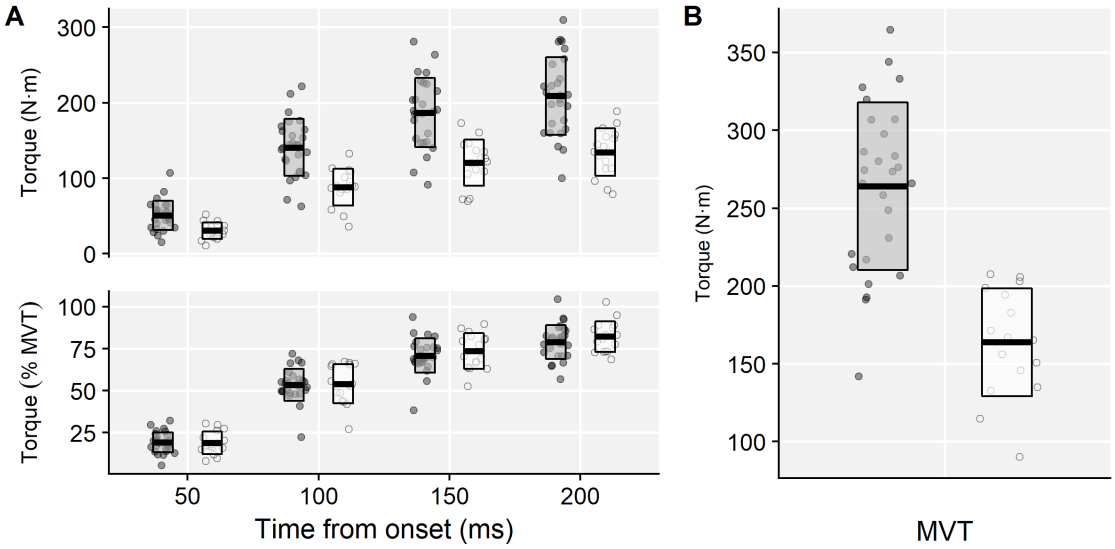

**Figure 3.11:** (A) Explosive performance at different time points of the time-torque curve expressed in absolute values (upper panel) and relative to maximal voluntary torque (lower panel). (B) Absolute maximal voluntary isometric torque (MVT). Horizontal thick lines within bars are mean and upper and lower bars edges represent standard deviation values.

Bonferroni correction was used in multiple bivariate Pearson's comparisons to avoid potential type I error. All data were analysed using R software (version 3.3.2, The R Foundation for Statistical Computing, 2016). Correlation coefficients were calculated and graphically displayed using the 'psych' (Revelle 2017) and 'corrplot' packages (Wei and Simko 2017), respectively.

## 3.3.2 Results

Descriptive data comprising maximal and explosive voluntary isometric torque performance is represented in Figure 3.11. FV profile and muscle architecture descriptive values are shown in Table 3.6. Despite greater $EMG_{MVIC}$ absolute values recorded on male *vs.* female (0.25 ± 0.12 *vs.* 0.14 ± 0.05 mV, respectively; F = 12.61, $p < 0.001$, $\eta^2_G = 0.24$), similar EMG normalised activation levels were observed during the explosive contractions (F = 0.00, p = 0.998, $\eta^2_G < 0.01$; Figure 3.12).

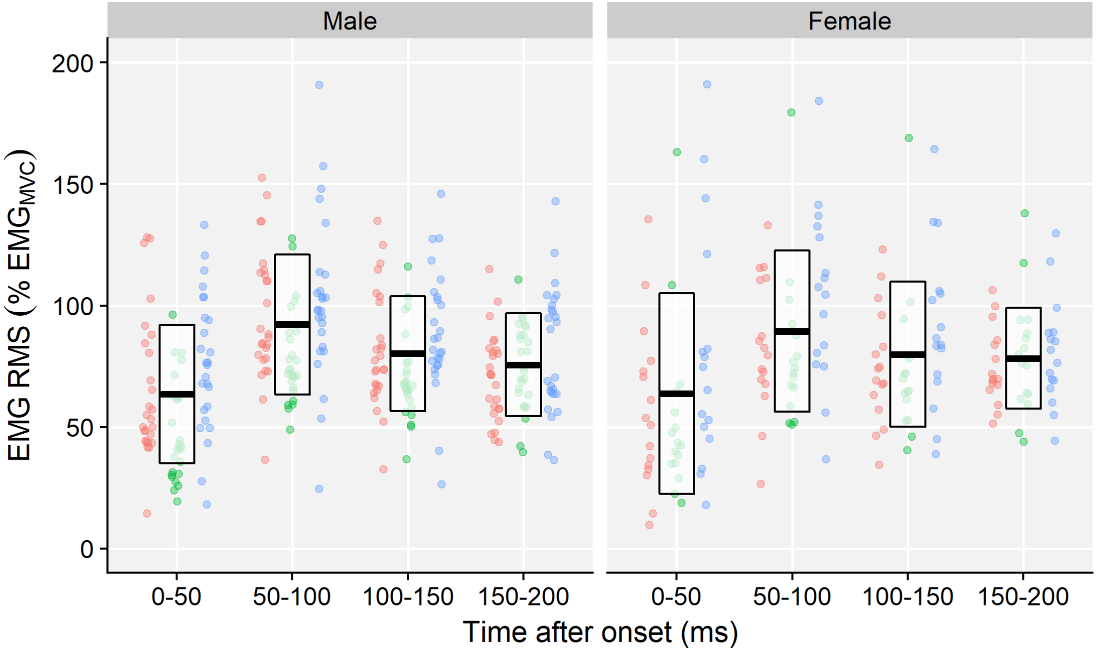

**Figure 3.12:** Muscle activation levels (i.e. root mean squared) normalised to the maximal muscle activation registered during MVC. Individual data values for each muscle are represented in red (rectus femoris), green (vastus lateralis) and blue dots (vastus medialis). Averaged (i.e. quadriceps) data is represented in the horizontal thick lines within bars (mean) and upper and lower bars edges (standard deviation).

**Table 3.6:** Descriptive data comprising FV profile and quadriceps architecture variables. Mean, standard deviation (SD) and between-participant coefficient of variation (CV) are shown for each corresponding variable.

| | Males (n = 27) | | Females (n = 16) | | All participants (n = 43) | |
|---|---|---|---|---|---|---|
| | Mean ± SD | CV % | Mean ± SD | CV % | Mean ± SD | CV % |
| **FV profile** | | | | | | |
| $F_0$ (N) | 2539.3 ± 377.4 | 14.9 | 1817.9 ± 276.6 | 15.2 | 2270.84 ± 489.89 | 21.6 |
| $V_0(m \cdot s^{-1})$ | 3.65 ± 0.80 | 21.9 | 3.20 ± 0.77 | 24.1 | 3.48 ± 0.81 | 23.3 |
| Slope | -738.69 ± 237.79 | 32.2 | -607.42 ± 202.49 | 33.3 | -689.85 ± 231.88 | 33.6 |
| $P_{max}$ (W) | 2280.35 ± 423.60 | 18.6 | 1433.95 ± 314.26 | 21.9 | 1965.41 ± 563.66 | 28.7 |
| **Muscle architecture** | | | | | | |
| Thickness (mm) | 24.01 ± 2.57 | 10.7 | 17.61 ± 2.1 | 11.9 | 21.63 ± 3.94 | 18.2 |
| VL p ang (deg) | 12.5 ± 1.4 | 11.5 | 9.7 ± 1.4 | 14.8 | 11.5 ± 1.9 | 17.3 |
| VL f length (mm) | 119.2 ± 22.6 | 18.9 | 113.3 ± 19.3 | 17.1 | 117.0 ± 21.4 | 18.3 |

The magnitude of the associations (i.e. coefficient of correlation) of $F_0$ and $P_{max}$ with voluntary explosive torque was found to increase from early phase explosive torque to MVIC torque. Pearson' correlation coefficients between the FV profile parameters and isometric torque variables are depicted in Figure 3.13. No meaningful relationships were found between any of the FV profile parameters and the isometric torque performance normalised to MVIC torque ($r \leq 0.07$, $p \geq 0.52$).

Moderate to large associations were observed between quadriceps muscle thickness and VL pennation angle with $F_0$ and $P_{max}$ , although no associations with $V_0$ or slope were found. Vastus lateralis fascicle length estimations showed no relationship with any of the FV profile parameters. Despite greater normalised EMG values observed in VM compared to VL and RF muscle ($F = 6.05$, $p = 0.003$, $\eta^2_G = 0.07$; Figure 3.12), no associations were found with any of the FV profile variables ($r < 0.01$). Likewise, no meaningful correlations were found between the FV relationship parameters and quadriceps EMG activation during the maximal or explosive contractions (Figure 3.14). Simple linear regressions showing associations between $F_0$ and MVIC torque, muscle thickness, pennation angle and $EMG_{MVIC}$ are shown in Figure 3.15.

Multiple linear regression models predicting $F_0$ from muscle architecture variables show that muscle thickness and pennation angle largely contributed to explain ~60% of the variance (Table 3.7). No meaningful improvements of $F_0$ predictions were observed when estimated VL fascicle length or $EMG_{MVIC}$ were added as predictors, as shown by no decrements in the Akaike information criterion (Table 3.7). No meaningful improvements in $F_0$ predictions were observed when gender was included as a predictor factor (Model 5 in Table 3.7).

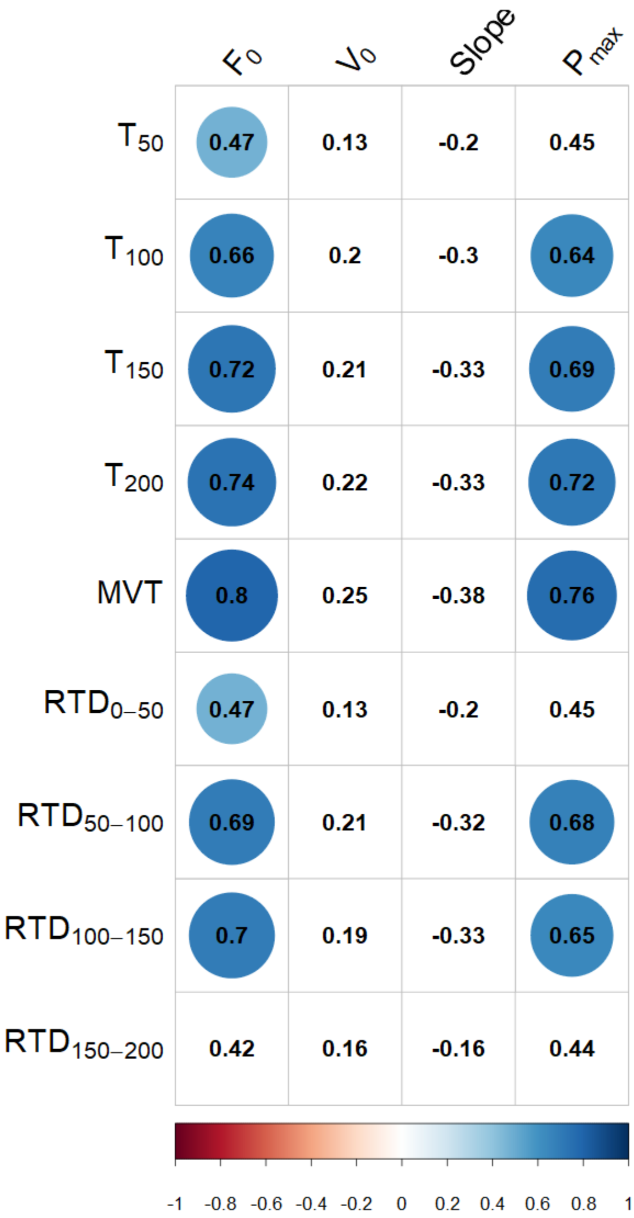

**Figure 3.13:** Correlation matrix figure showing r Pearson coefficients between the FV profile variables [maximum theoretical force (F0), maximum theoretical velocity (V0), slope of the relationship and maximum theoretical power (Pmax)] and isometric torque performance [explosive torque (T50, T100, T150, T200), sequential rate of force development (RTD0-50, RTD50-100, RTD100-150, RTD150-200) and maximum voluntary isometric torque (MVIC)]. Coloured circles indicate $p < 0.05$ and circle size and colour illustrate r values (colour legend shown at the bottom of the figure).

**Figure 3.14:** Pearson's correlation coefficients between functional (FV profile and isometric torque related variables variables) and muscle structural (quadriceps thickness and vastus lateralis pennation angle and fascicle length) and voluntary quadriceps activation (EMG$_{MVIC}$, EMG$_{0\text{-}50}$, EMG$_{50\text{-}100}$, EMG$_{100\text{-}150}$, EMG$_{150\text{-}200}$) parameters. Coloured circles indicate $P < 0.05$ and circle size and colour illustrate $r$ values (colour legend shown at the bottom of the figure).

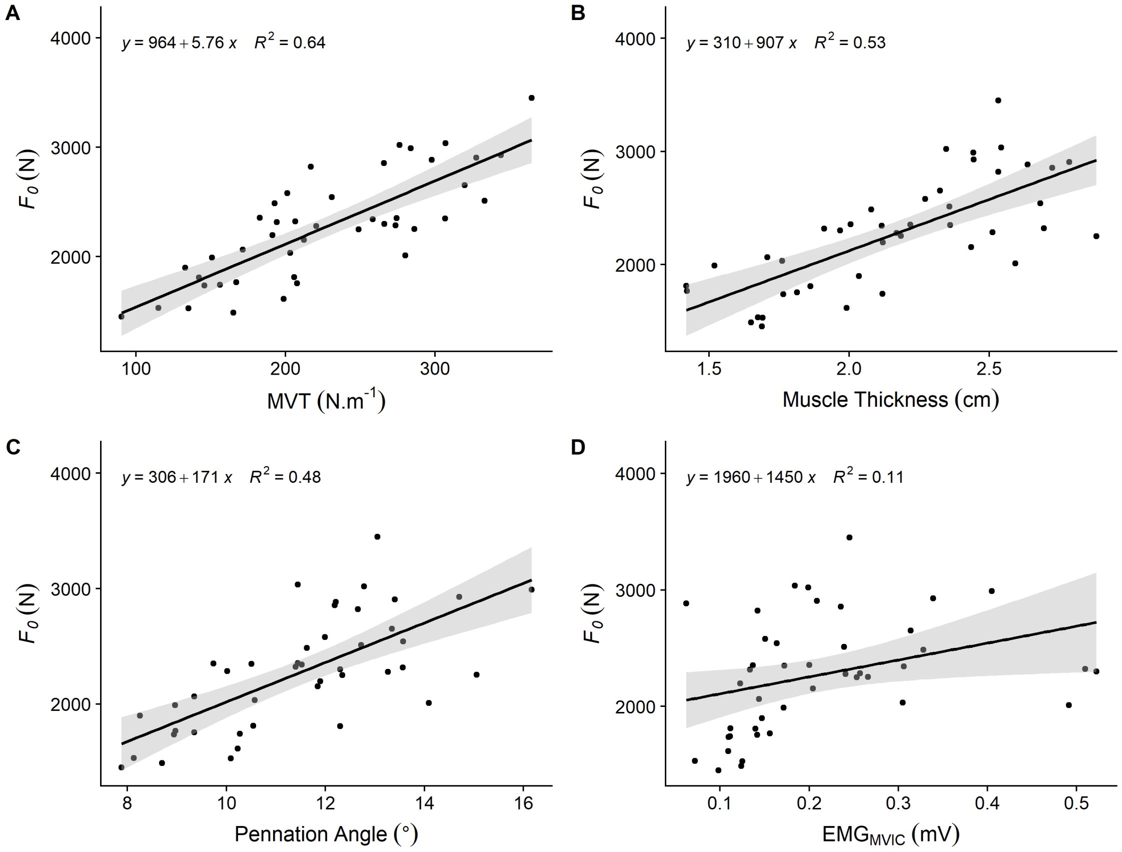

**Figure 3.15:** Scatterplots showing simple linear regressions predicting maximal theoretical force ($F_0$) from (A) maximum voluntary isometric torque (MVIC), (B) muscle thickness, (C) pennation angle and (D) absolute EMG activation during MVIC ($EMG_{MVIC}$).

**Table 3.7:** Multiple linear regression models predicting maximal theoretical force (F0) using maximal voluntary torque (MVT), quadriceps muscle morphology (i.e. averaged muscle thickness and VL pennation angle), EMG activation during MVT (EMGMVC) and Gender as predictor variables.

| | Model 1 | | Model 2 | | Model 3 | | Model 4 | | Model 5 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Estimate (CI) | std error | Estimate (CI) | std error | Estimate (CI) | std error | Estimate (CI) | std error | Estimate (CI) | std error |
| (Intercept) | 309.74 (-281.39 – 900.86) | 292.7 | -134.35 (-744.48 – 475.78) | 301.88 | -312.03 (-1023.81 – 399.74) | 351.89 | -331.44 (-1056.02 – 393.14) | 357.93 | 615.83 (-928.62 – 2160.29) | 762.24 |
| Muscle Thickness | 90.67 (63.77 – 117.57) *** | 13.32 | 60.26 (28.81 – 91.71) *** | 15.56 | 48.46 (8.71 – 88.21) * | 19.65 | 50.15 (9.29 – 91.00) * | 20.18 | 31.01 (-17.93 – 79.95) | 24.15 |
| Pennation Angle | | | 96.03 (33.60 – 158.47) ** | 30.89 | 113.14 (41.42 – 184.86) ** | 35.46 | 117.81 (42.50 – 193.12) ** | 37.2 | 102.32 (24.59 – 180.05) * | 38.36 |
| Fascicle length | | | | | 30.25 (-31.95 – 92.45) | 30.75 | 27.61 (-36.31 – 91.54) | 31.58 | 29.91 (-33.36 – 93.18) | 31.23 |
| EMGMVIC | | | | | | | -236.27 (-1264.96 – 792.43) | 508.15 | -364.69 (-1398.22 – 668.85) | 510.09 |
| Gender | | | | | | | | | -252.5 (-617.24 – 112.25) | 180.01 |
| N | 43 | | 43 | | 43 | | 43 | | 43 | |
| R2 / adj. R2 | .53 / .52 | | .62 / .60 | | .63 / .60 | | .63 / .59 | | .65 / .60 | |
| F-statistics | 46.34*** | | 32.90*** | | 22.24*** | | 16.40*** | | 13.85*** | |
| AIC | 627.2 | | 619.89 | | 620.84 | | 622.59 | | 622.37 | |
| RSE | 339.7 | | 308.7 | | 308.8 | | 311.9 | | 308.1 | |

Akaike information criterion (AIC). Residual Standard Error (RSE). 95% Confidence Interval (CI) * p<0.05 ** p<0.01 ***p<0.001

### 3.3.3 Discussion

The current investigation examined relationships between the FV profile and isometric strength performance during a knee extension task. The influence of quadriceps muscle architecture and voluntary muscle activation on the FV profile was also evaluated. The main findings showed meaningful relationships between isometric torque, maximal theoretical force ($F_0$) and power ($P_{max}$) from the FV test and quadriceps muscle architecture (i.e. quadriceps thickness and VL pennation angle). On the contrary, $V_0$ showed no associations with any of the isometric strength or muscle physiological measurements.

Associations of $F_0$ and $P_{max}$ with isometric torque were found to gradually increase from early to late phase explosive performance and were even stronger with MVIC torque (Figure 3.13). Similarly, Driss et al (2002) showed meaningful relationships between $F_0$, obtained during a FV test conducted on a leg cycle ergometer, and the maximal isometric strength of the knee extensors. These findings support earlier observations on the agreement between dynamic and isometric maximal strength measurements (McGuigan and Winchester 2008; Haff et al. 1997) and may be of interest for practitioners carrying out different maximal strength assessments. Interestingly, and despite of the complex nature of loaded jumping tasks (Giroux et al. 2015), our results suggest that the maximal theoretical force estimated from the FV relationship ($F_0$) during the CMJ exercise, is highly determined by the maximal isometric strength as well as the size of the knee extensors. The fact that a FV profiling procedure may comprise multiple loading conditions likely explains the observed agreement between dynamic and isometric maximal strength estimates, which supports the use of multiple-load FV assessments as opposed to single-load testing procedures (Jaric 2015). Indeed, studies showing no correlation between dynamic and isometric strength measurements have usually comprised single low-load dynamic tasks such as jumping (de Ruiter et al. 2006; Wilhelm et al. 2013) or throwing (Murphy and Wilson 1996). Nonetheless, and despite the meaningful relationships observed among maximal strength indexes, the evidence regarding associations of dynamic *vs.* isometric explosive performance remains conflictive (de Ruiter et al. 2006; Driss et al. 2002; de Ruiter et al. 2007).

Our results showed no meaningful relationships between $V_0$ and any of the isometric torque measurements, pointing out the relevance of task specificity when it comes to assessing muscle explosive performance (Baker, Wilson, and Carlyon 1994; de Ruiter et al. 2007). Previous investigations showing meaningful links between isometric explosive force and sprint performance have employed multi-joint isometric tasks (i.e. squat, mid-thigh pull, etc.) as opposed to the single joint test used in our study (Tillin, Pain, and Folland 2013a; Thomas et al. 2016). The high variability reported in early phase isometric strength measurements (Folland, Buckthorpe, and Hannah 2014) as well as the weak influence of $V_0$ on the overall FV profile performance (i.e. $P_{max}$) assessed in the CMJ exercise (Cuk et al. 2016) may explain the lack of association found between $V_0$ and any other parameter in the current study. Loading conditions during a typical FV test using the CMJ exercise are inherently closer to $F_0$ than $V_0$, which may thus provide specific information about the maximal strength capabilities (Cuk et al. 2016). Notwithstanding, $V_0$ has also been previously described to be unrelated with isometric strength performance when estimated from a cycle ergometer-based FV test (Driss et al. 2002). The highly movement-specific neural activation patterns and their significance in the early phase of explosive movements (Buckthorpe et al. 2012) may be responsible for the lack of association between different explosive performance measures.

Muscle explosive force generating capabilities have been shown to be significantly influenced by both, the nervous system ability to quickly activate muscles (Andersen and Aagaard 2006; Aagaard 2003) and the muscle morphology (Lieber and Fridén 2000). Nevertheless, no associations between early neural voluntary activation and any of the FV profile parameters were observed in this experiment. Only absolute EMG signal amplitude values during MVIC were linked to some extent with $F_0$ and $P_{max}$ ($r > 0.31$), but unrelated to $V_0$ and slope. On the other hand, greater quadriceps thickness and VL pennation angles were observed on participants with higher $F_0$ values, highlighting the well-known influence of muscle size on the muscle force generating capabilities (Folland and Williams 2007; Lieber and Fridén 2000), and the specific contribution of the quadriceps femoris muscle during jumping actions (Giroux et al. 2015). Estimations of VL fascicle length, however, showed no meaningful associations with any of the FV profile parameters. Similarly, previous research has shown a weak influence of VL fascicle length on the quadriceps torque performance at higher angular velocities (Blazevich et al. 2009). Despite the theoretical (Lieber and Fridén 2000) and experimental (Kumagai et al. 2000) evidence positively relating muscle fascicle length with shortening velocity, these and previous findings (Blazevich et al. 2009) highlight the complexity of the neuromuscular system, whose performance is determined by multiple mechanisms interacting each other (Trezise, Collier, and Blazevich 2016). The fact that fascicle length and pennation angles are often measured at very specific muscle regions (i.e. VL mid-high), where fascicles and aponeuroses present linear geometry, may limit our understanding of the truly complex muscle architecture influence on performance. In this context, the use of new ultrasound imaging techniques such as the extended-field-of-view imaging mode (i.e. panoramic) (Noorkoiv, Nosaka, and Blazevich 2010) may help to obtain a better insight of the intra and inter-muscular variation of the resting quadriceps femoris muscle architecture, and its influence on ballistic tasks. Moreover, readers should be aware that other important biomechanical factors not comprised in the present study, such as the muscle-tendon unit elastic properties (Roberts 2016) or its mechanical behaviour during jumping (Earp et al. 2017) would have helped to comprehensively examine the associations explored in this study.

Several important points should also be considered when interpreting the results of the present investigation. Firstly, the specific FV testing procedures employed (i.e. loaded CMJ exercise) likely influenced the nature of the observed correlations. The inclusion of unloaded conditions (i.e. negative loading conditions) (Cuk et al. 2016) in the FV test could yield different results, notably regarding the determinants of $V_0$, and may be considered in future research. Secondly, the use of task-specific isometric testing procedures (i.e. isometric squatting) could also help gaining further understanding of the associations explored here. Lastly, it should be considered that the conflictive evidence regarding cross-sectional associations between dynamic and isometric strength measurements has been often linked to the degree of homogeneity of the study sample (i.e. level of training, gender, etc). Our sample comprised physically active males and females and consequently these results do not directly translate to other specific trained populations (i.e. elite athletes from a specific sport discipline). Despite the potential gender influence on neuromuscular performance (Bell and Jacobs 1986), no differences were observed in the normalised variables (i.e. torque and EMG during explosive contractions) and no meaningful improvements in $F_0$ predictions were observed when gender was included as a predictor variable.

In conclusion, the present investigation shows that the maximal theoretical force ($F_0$), obtained from a FV profiling test during the CMJ exercise, is positively related with the knee extensors muscles maximal isometric strength, quadriceps thickness and VL pennation angle. On the contrary, the lack of association of $V_0$ with explosive isometric performance, voluntary neural activation and muscle morphological factors support previous findings reporting a weaker contribution of $V_0$ in the overall FV profile performance ($P_{\text{max}}$) compared to $F_0$, for this particular exercise (Cuk et al. 2016). These findings may provide practitioners with a deeper insight into the mechanisms of the FV profile parameters and their association with commonly employed maximal and explosive isometric strength testing procedures.

## 3.4 Study 4: Acute effects of moderate altitude on performance and lower-body muscle activation during resistance training

### 3.4.1 Methods

#### Overview

A repeated measures design was employed to evaluate the effects of external load (i.e. heavy *vs.* light load) and altitude (i.e. normoxia *vs.* moderate altitude) on the dependent variables derived from ground reaction force (GRF) and surface electromyography (EMG) signals recorded during isometric and countermovement jump (CMJ) efforts. Participants took part of five laboratory testing sessions. On day one, participants carried out an incremental loading test during the CMJ exercise as well as a familiarization protocol with isometric squats and continuous CMJs. Based on the individual load-velocity linear relationship, a heavy and a light loading condition was determined as the external load associated with a mean propulsive velocity of 1.1 and 1.4 $m \cdot s^{-1}$, respectively. These velocities have been previously shown to correspond to ~45% and ~20% 1RM during the CMJ exercise (Pérez-Castilla, García-Ramos, et al. 2017). The remaining four assessment sessions comprised performing two squat MVIC followed by a protocol of six sets of six CMJ repetitions at the corresponding loading (i.e. heavy, light) and altitude condition (i.e. hypoxia: 2320 m asl, normoxia: 690 m), in a counterbalanced randomized order. Ground reaction force (GRF) and surface electromyography (EMG) were recorded during all efforts. Oxygen arterial saturation ($SaO_2$) and ratings of perceived exertion (RPE) were measured before and after each testing session, respectively.

## Participants

Twelve participants were recruited to participate in this study. Body weight, height and age were 76.1 ± 8.5 kg, 176.8 ± 6.6 cm and 23.6 ± 5.8 years, respectively. All individuals vervally reported systematic resistance training of the lower-body muscles. The study was approved by the university's Ethical Advisory Committee and all subjects signed an informed consent in accordance with the Declaration of Helsinki.

## Testing procedures

### CMJ incremental loading test and familiarization session

Following a standardized warm-up protocol (5 min cycling, joint mobility exercises and 4 unloaded CMJs), participants performed two CMJ repetitions (1 min rest between them) at four absolute loading conditions (20, 40, 60 and 80 kg). Three-minute rests were kept between loads. Participants were asked to maintain constant downward pressure on the barbell and to jump as high as possible. A manual goniometer and an adjustable rod on a tripod were used to set CMJ depth to 90º knee angle for each subject. At each load, the repetition with the highest mean propulsive velocity was used to construct a linear load-velocity relationship. For each participant, the external loads corresponding to a mean propulsive velocity of 1.1 and 1.4 m·s$^{-1}$, for the heavy and light loading conditions, respectively, were estimated from the load-velocity relationship. Afterwards, participants were familiarized with the assessment protocol by performing four 3-5 s isometric squats and two sets of six repetitions at the corresponding heavy and light loading conditions.

### Arterial oxygen saturation ($SaO_2$)

During each of the four assessment sessions, and fifteen minutes upon arrival to the laboratory, resting $SaO_2$ levels were assessed using a pulse oximeter device (Onyx Vantage 9590, Nonin, Plymouth, MN, USA). Two measurements were taken and averaged for further analyses.

### Maximal voluntary isometric contraction (MVIC)

Isometric squats were performed using a fixed Smith Machine (Multipower Fitness Line, Peroga, Murcia, Spain) and a force plate (KI 9253B11, Kistler, Switzerland) to record GRF. Barbell height was set at 75% of the participant's height (Tillin, Pain, and Folland 2013a); the Smith Machine system allowed it to be adjusted in ~1 cm increments. Following a warm-up protocol comprising three submaximal contractions at 50%, 75% and 90% of perceived maximal MVIC, participants completed two maximal contractions separated by 1 min. During each attempt, participants were encouraged to push as hard as possible for 3-5 s. The highest vertical GRF value was taken as maximal voluntary isometric force (MVIF).

### CMJ protocol

Five minutes after the MVIC repetitions and preceded by a specific standardized warm-up (5 min cycling, joint mobility exercises, 4 unloaded CMJs and 2 sets of 3 repetitions with half of the corresponding load), participants completed six sets of six CMJ repetitions (3 min between sets) at the corresponding external loading condition. A metronome was used to keep constant execution pace (i.e. 1 repetition every 3 seconds). GRF and surface EMG signals were registered during all repetitions. Participants were instructed to perform every repetition at maximum intended velocity. CMJ technique involved participants to perform the downwards phase in a controlled manner, to jump as high as possible and to recover their initial position, marked on the force plate device, after each CMJ repetition.

## Data collection and processing

### Mechanical variables

GRF was recorded and sampled at 1kHz using a force plate (Type 9260AA6, Kistler, Switzerland). The system center of mass (COM) velocity was calculated from $F_z$ GRF and used to identify the concentric part of the movement. Precisely, net GRF was first calculated by subtracting the system weight and then divided by the system mass to provide acceleration. Thereafter, acceleration was numerically integrated to provide instantaneous COM velocity. The concentric movement phase was defined from the onset of upward motion (i.e. instantaneous COM velocity $> 0$ m·s$^{-1}$) to the take-off instant (i.e. GRF $< 5$ N). Peak force, velocity and power during each repetition were averaged across sets and used for further statistical analyses. Additionally, the complete force-, velocity- and power-time curves from each repetition, averaged across sets and participants and time-normalized, were plotted for presentation purposes.

### Surface Electromyography

EMG activity was recorded wirelessly from the vastus medialis (VM), vastus lateralis (VL), rectus femoris (RF), biceps femoris (BF) and gastrocnemius medialis (GM) muscles (Delsys, Boston, Massachusetts, USA). Both EMG and GRF signals were synchronously recorded using an external trigger module (Delsys, Boston, Massachusetts, USA). Raw EMG signals were amplified (× 1000) and sampled at 2 kHz. After skin preparation (shaving, light abrasion and cleaning with alcohol), EMG surface electrodes (Trigno Standard Sensor; Delsys Boston, Massachusetts, USA) were placed according to the surface EMG for non-invasive assessment of muscle recommendations (Hermens et al. 2000). EMG electrodes were firmly taped to the skin to minimize movement artifacts during jumps, and electrode positions were marked on the skin to be reproduced across sessions. EMG signals were first band-pass-filtered (10-400 Hz, 6th order Butterworth filter) for smoothing purposes and to remove any DC offset. Then, the root mean square (RMS; Equation (3.5)), median frequency ($F_{med}$; Equation (3.6)) and the spectral parameter proposed by Dimitrov et al. (2006) with spectral moment order 5 ($FI_{nsm5}$; Equation (3.7)) was calculated over the concentric phase of each CMJ repetition for each muscle. The changes in values of each EMG parameter (RMS, $F_{med}$, $FI_{nsm5}$) were normalized to the first repetition of each set.

### Ratings of perceived exertion (RPE)

Fiveteen minutes following each assessment session, participants were asked to rate their session perceived exertion (RPE) using a 10-point visual scale.

### Statistical analyses

All statistical analyses were performed using R software (version 3.3.2, The R Foundation for Statistical Computing, 2016). Normal distributions of the data were confirmed using a Shapiro-Wilk test. Two separate one-way analysis of variance (ANOVA) were used to evaluate the effects of altitude on $SaO_2$ and MVIF. A two-way ANOVA was computed to evaluate the effects of load and altitude on RPE. Additionally, separate three-way ANOVAs were computed to explore the effects of load (heavy *vs.* light), altitude (hypoxia *vs.* normoxia) and repetition (i.e. repetition 1 *vs.* 2, 3, 4, 5 and 6) on the force-plate derived mechanical variables (force, velocity and power). Four-way separate ANOVAs were computed to evaluate the effects of load, altitude, repetition and muscle (VL, RF, VM, BF and GM) on each EMG-derived parameter (RMS, $F_{med}$ and $FI_{nsm5}$). When the sphericity assumption in ANOVAs was violated (Mauchly's test), a Geisser-Greenhouse correction was used. Post-hoc tests were performed by means of Bonferroni procedures when appropriate for multiple comparisons. Alpha was set at 0.05. Generalized Eta-Squared measures of effect size and thresholds (0.02 [small], 0.13 [medium] and 0.26 [large]) were calculated along with ANOVA effects (Bakeman 2005). ANOVAs were performed using the 'ez' (Lawrence 2016) R package. Cohen's d effect sizes and thresholds (>0.2 [small], >0.6 [moderate], >1.2 [large] and >2 [very large]) were also calculated on all dependent variables to observe the magnitude of the standardized mean differences, using the 'mbir' (Peterson 2017) package and the following Equation (3.10):

$$Cohen's\ d = \frac{M_1 - M_2}{\sqrt{\frac{SD_1^2 + SD_2^2}{2}}} \tag{3.10}$$

## 3.4.2 Results

### Arterial oxygenation

There was a large main effect of altitude on $SaO_2$ ($F = 251.25$, $p < 0.001$, $\eta_G^2 = 0.94$) due to lower values at moderate altitude compared to normoxic conditions (92.7 ± 0.7 *vs.* 97.8 ± 0.6%).

### Ratings of perceived exertion

No main effect of altitude was observed ($F = 1.10$, $p = 0.318$, $\eta_G^2 = 0.01$). A main effect of load ($F = 68.02$, $p < 0.001$, $\eta_G^2 = 0.43$) and an altitude × load interaction effect ($F = 5.30$, $p = 0.042$, $\eta_G^2 = 0.05$) were observed on RPE due to greater values during the heavy load session at altitude ($p = 0.01$; Figure 3.16).

### Maximal voluntary contractions

There was no main effect of altitude on MVIF (3434.3 ± 568.3 *vs.* 3440.4 ± 608.2 N, at moderate altitude and normoxia, respectively; $F = 0.02$, $p = 0.900$, $\eta_G^2 < 0.01$). Similarly, no effect of altitude was observed on $EMG_{\mathrm{MVIC}}$ ($F = 0.04$, $p = 0.842$, $\eta_G^2 < 0.01$).

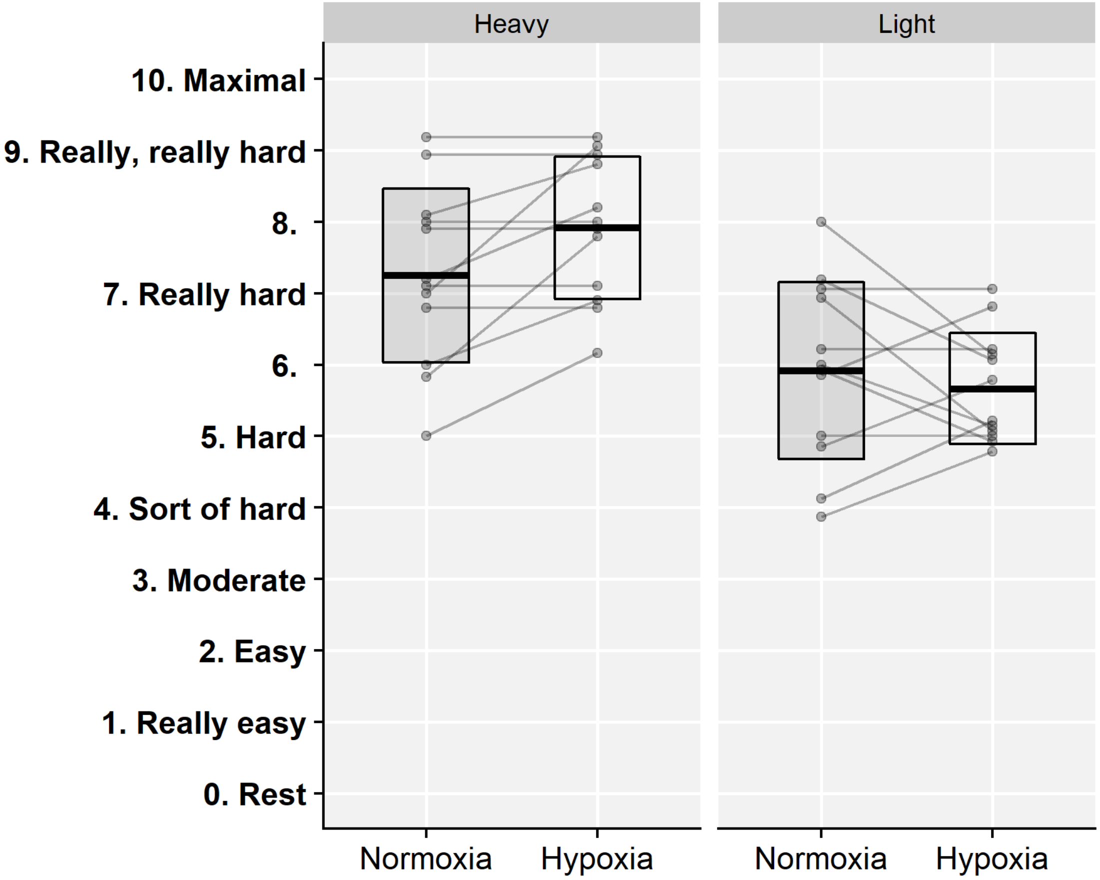

**Figure 3.16:** Ratings of perceived exertion values following the CMJ training session at normoxia or hypoxia, under heavy or light loading conditions. ANOVA showed main effects of load and a load × altitude interaction effect due to slightly greater RPE values during the heavy condition at altitude.

### Mechanical performance

There were *large* main effects of load on force ($F$ = 221.65, p < 0.001, $\eta^2_G$ = 0.24) and velocity ($F$ = 413.20, p < 0.001, $\eta^2_G$ = 0.75) due to greater force (2444.3 ± 244.2 *vs.* 2192.3 ± 220.7 N) and lower velocity values (1.71 ± 0.08 *vs.* 2.03 ± 0.10 $\mathrm{m} \cdot \mathrm{s}^1$) in the heavy *vs.* light conditions, respectively. A main effect of load was observed on power output ($F$ = 14.60, $p$ = 0.003, $\eta^2_G$ = 0.03) due to greater values during the light loading conditions (3741.4 ± 464.5 *vs.* 3903.3 ± 451.3 W). As shown in Figure 3.17, main effects of repetition were observed due to decrements in force, velocity and power across repetitions (force: $F$ = 34.27, p < 0.001, $\eta^2_G$ = 0.02; velocity: $F$ = 92.66, p < 0.001, $\eta^2_G$ = 0.21; power: $F$ = 103.64, p < 0.001, $\eta^2_G$ = 0.11). *Small* load × repetition interaction effects were observed on force ($F$ = 3.75, $p$ = 0.048, $\eta^2_G$ < 0.01), velocity ($F$ = 3.17, $p$ = 0.026, $\eta^2_G$ < 0.01) and power output ($F$ = 3.58, $p$ = 0.023, $\eta^2_G$ < 0.01) due to slightly greater decrements across repetitions during the heavy condition.

No main effect of altitude was observed on force ($F$ = 1.90, $p$ = 0.196, $\eta^2_G$ < 0.01; Figure 3.18), velocity ($F$ = 0.16, $p$ = 0.700, $\eta^2_G$ < 0.01; Figure 3.19) or power ($F$ = 0.26, $p$ = 0.623, $\eta^2_G$ < 0.01; Figure 3.20). *Small* altitude × load × repetition interaction effects were observed on force ($F$ = 5.75, $p$ = 0.002, $\eta^2_G$ < 0.01), velocity ($F$ = 7.47, $p$ < 0.001, $\eta^2_G$ < 0.01) and power output ($F$ = 8.60, $p$ < 0.001, $\eta^2_G$ < 0.01) due to greater decrements across repetitions in the heavy conditions at moderate altitude and greater decrements during the light loading conditions at normoxia (Figure 3.19).

### Muscle activation

No main effect of altitude was observed on RMS ($F$ = 3.07, $p$ = 0.108, $\eta^2_G$ < 0.01), $\mathrm{F}_{\mathrm{med}}$ ($F$ = 3.84, $p$ = 0.076, $\eta^2_G$ < 0.01) or $\mathrm{FI}_{\mathrm{nsm5}}$ ($F$ = 0.03, $p$ = 0.859, $\eta^2_G$ < 0.01). There was a small main effect of repetition on RMS ($F$ = 4.54, $p$ = 0.002, $\eta^2_G$ < 0.01), $\mathrm{F}_{\mathrm{med}}$ ($F$ = 11.36, p < 0.001, $\eta^2_G$ = 0.01) and $\mathrm{FI}_{\mathrm{nsm5}}$ ($F$ = 7.15, p < 0.001, $\eta^2_G$ < 0.01) and a main effect of muscle on RMS ($F$ = 35.76, p < 0.001, $\eta^2_G$ = 0.72), $\mathrm{F}_{\mathrm{med}}$ ($F$ = 32.97, p < 0.001, $\eta^2_G$ = 0.67) and $\mathrm{FI}_{\mathrm{nsm5}}$ ($F$ = 5.68, p < 0.001, $\eta^2_G$ = 0.30). A main effect of loading condition occurred on $\mathrm{F}_{\mathrm{med}}$ ($F$ =

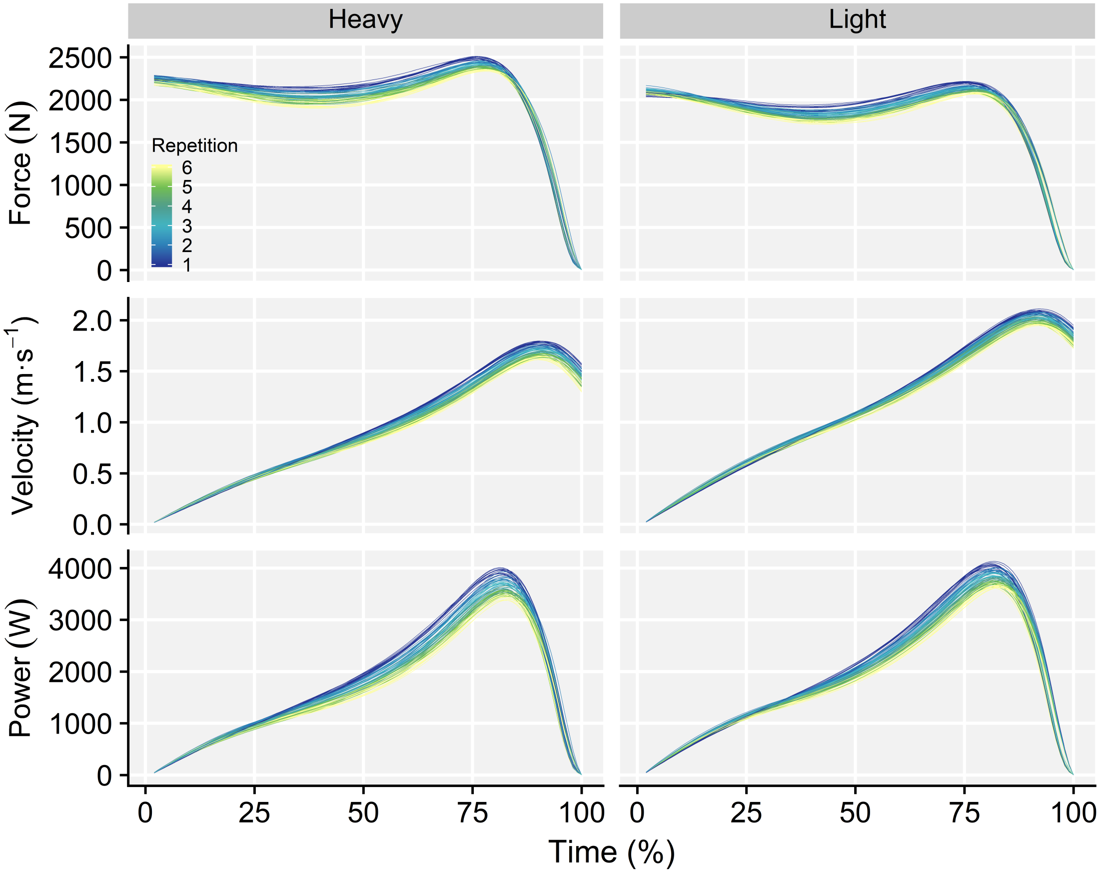

**Figure 3.17:** Force, velocity and power-time curves of the concentric phase of the CMJ repetitions registered during training under heavy and light external loading conditions. For presentation purposes, repetitions (i.e. from 1 to 6) were averaged across sets and altitude conditions, and time normalized (i.e. from 0 to 100% of total repetition time). The colour scale indicates each repetition and illustrates the performance decrement observed during a typical training session.

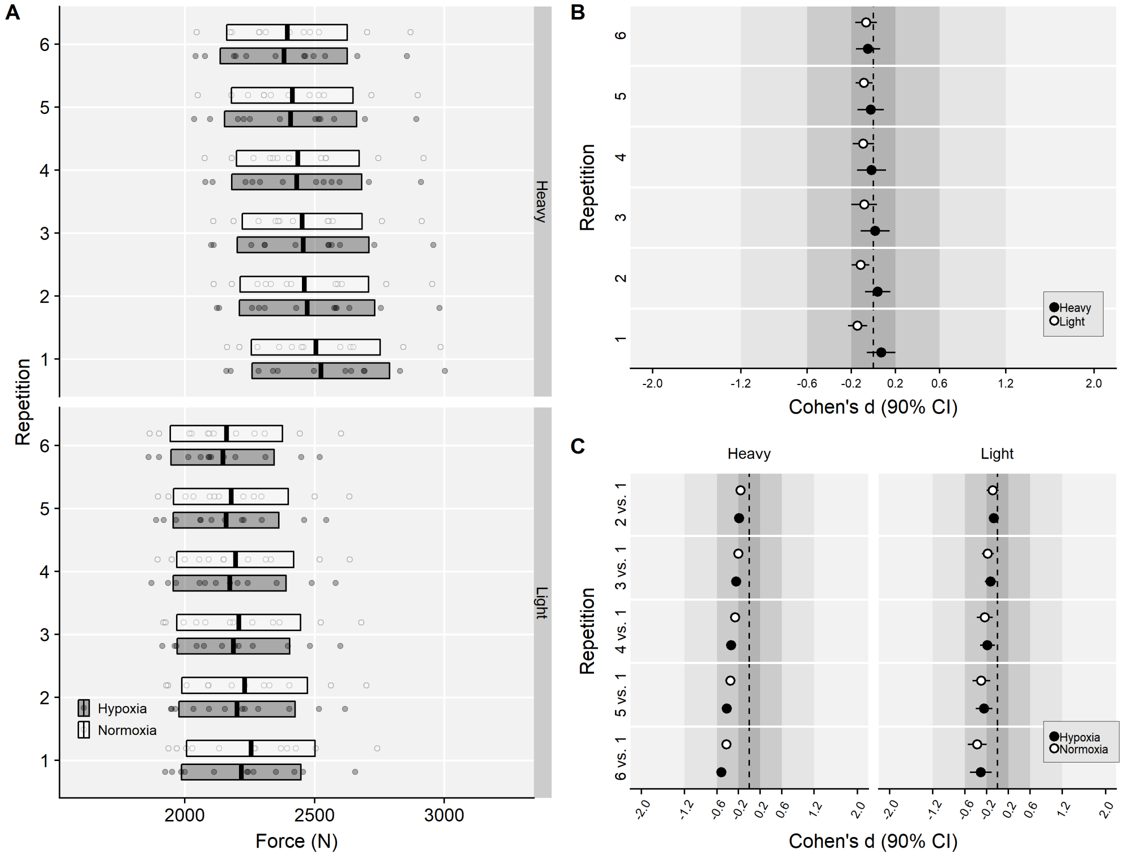

**Figure 3.18:** Ground reaction forces. (A) Ground reaction force values, averaged across sets, during the light and heavy loading conditions at normoxia or hypoxia. Horizontal thick lines within bars are mean and upper and lower bars edges are standard deviation. Individual observations are shown as grey or white circles, respectively. (B) Standardized mean differences (90% confidence intervals) between normoxia and hypoxia at each corresponding loading condition. Positive and negative values denote greater values in hypoxia or normoxia, respectively. (C) Standardized mean differences (90% confidence intervals) from repetition 1 at each loading and altitude condition. Negative effect sizes denote lower values than repetition 1, for each loading and altitude condition.

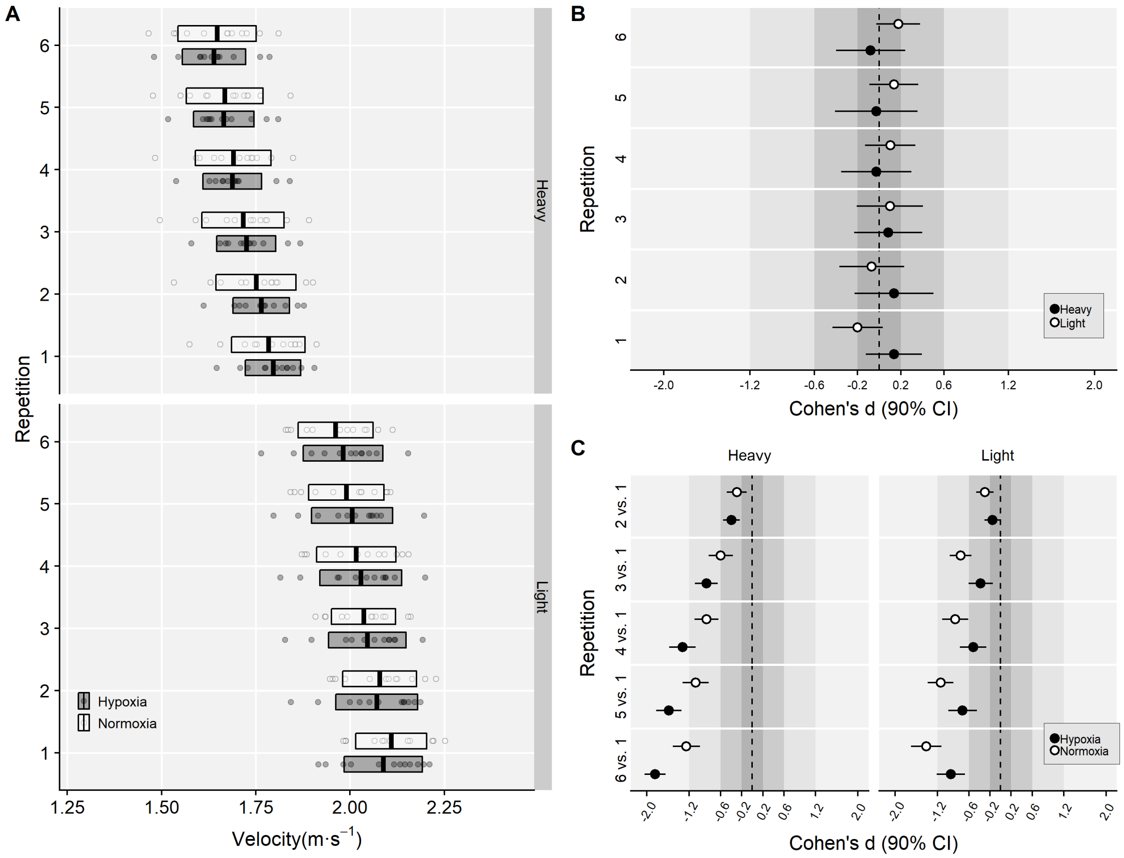

**Figure 3.19:** Center of mass velocity results. (A) Peak velocity values, averaged across sets, during the light and heavy loading conditions at normoxia or hypoxia. Horizontal thick lines within bars are mean and upper and lower bars edges are standard deviation. Individual observations are shown as grey or white circles, respectively. (B) Standardized mean differences (90% confidence intervals) between normoxia and hypoxia at each corresponding loading condition. Positive and negative values denote greater values in hypoxia or normoxia, respectively. (C) Standardized mean differences (90% confidence intervals) from repetition 1 at each loading and altitude condition. Negative effect sizes denote lower values than repetition 1, for each loading and altitude condition.

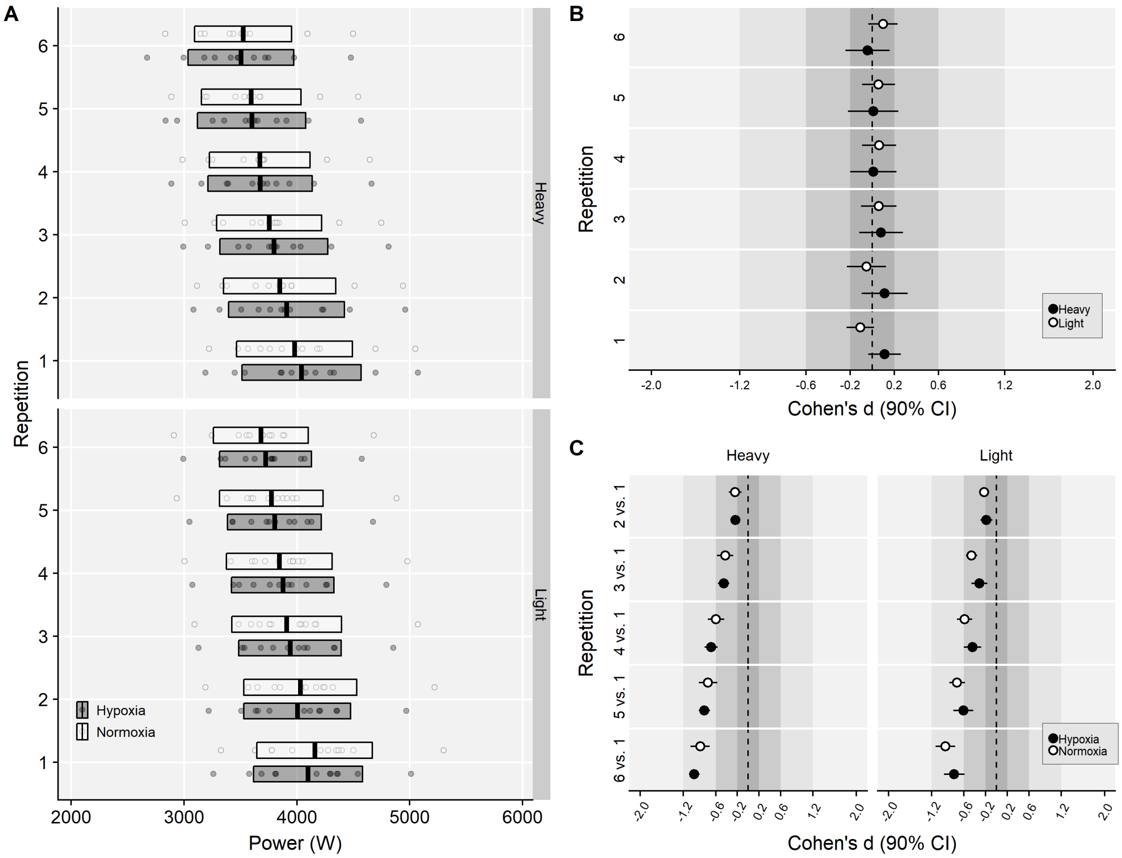

**Figure 3.20:** Power output results. (A) Power output values, averaged across sets, during the light and heavy loading conditions at normoxia or hypoxia. Horizontal thick lines within bars are mean and upper and lower bars edges are standard deviation. Individual observations are shown as grey or white circles, respectively. (B) Standardized mean differences (90% confidence intervals) between normoxia and hypoxia at each corresponding loading condition. Positive and negative values denote greater values in hypoxia or normoxia, respectively. (C) Standardized mean differences (90% confidence intervals) from repetition 1 at each loading and altitude condition. Negative effect sizes denote lower values than repetition 1, for each loading and altitude condition.

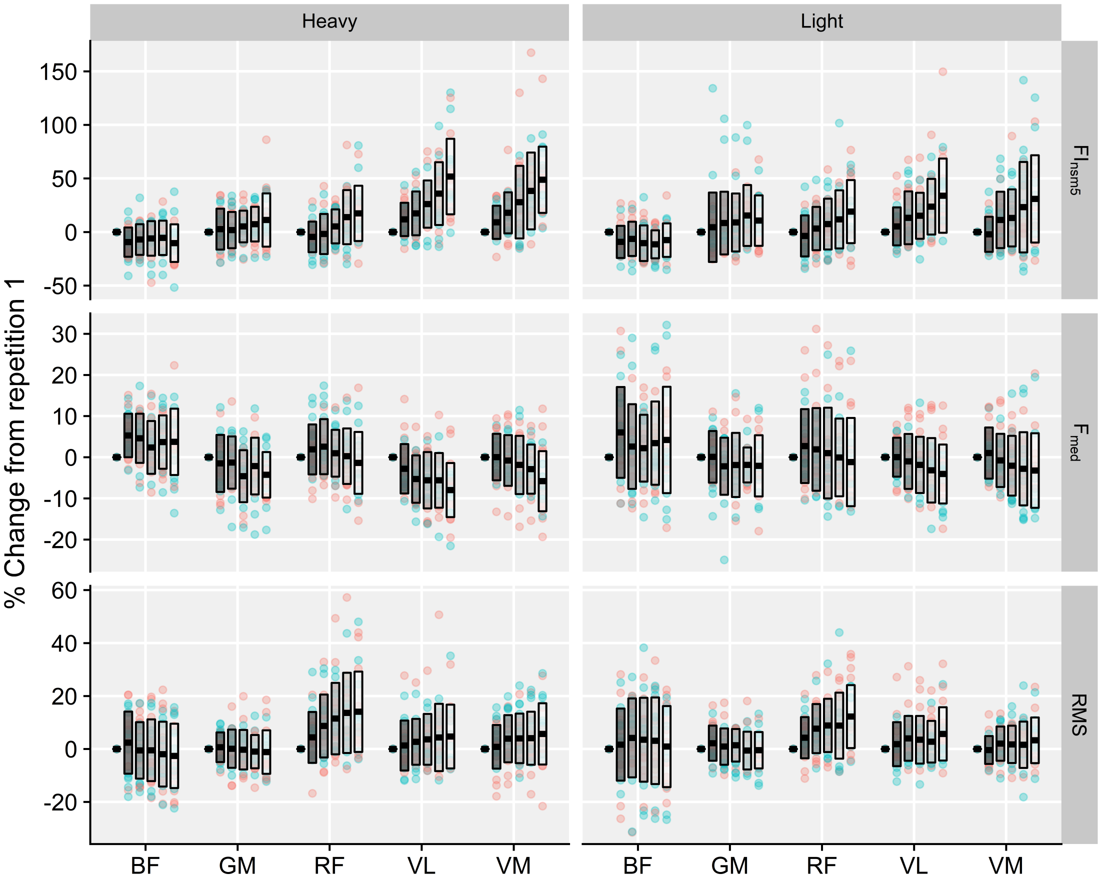

**Figure 3.21:** Relative changes from the first repetition in the electromyography derived variables (RMS, $F_{med}$ and $FI_{nsm5}$) for each corresponding muscle (biceps femoris (BF), gastrocnemius medialis (GM), rectus femoris (RF), vastus lateralis (VL) and vastus medialis (VM)) and loading condition. Horizontal thick lines within bars are mean and upper and lower bars edges are standard deviation. Individual observations are shown as red or blue circles, for hypoxia and normoxia, respectively. ANOVA showed no differences between altitude conditions.

6.17, $p = 0.030$, $\eta^2_G < 0.01$) but not on RMS ($F = 2.54$, $p = 0.139$, $\eta^2_G < 0.01$) or $FI_{nsm5}$ ($F = 0.99$, $p = 0.341$, $\eta^2_G < 0.01$).

Regardless the environmental condition, *small* muscle × repetition interaction effects were observed on RMS ($F = 4.24$, p $< 0.001$, $\eta^2_G < 0.01$), $F_{med}$ ($F = 3.10$, p $< 0.001$, $\eta^2_G < 0.01$) and $FI_{nsm5}$ ($F = 4.11$, p $< 0.001$, $\eta^2_G < 0.01$) due to significant changes in VL, VL and RF muscles across repetitions (Figure 3.21 and 3.22). No significant altitude × load × repetition interaction effects were observed on RMS ($F = 0.71$, $p = 0.620$, $\eta^2_G < 0.01$), $F_{med}$ ($F = 0.70$, $p = 0.624$, $\eta^2_G < 0.01$) or $FI_{nsm5}$ ($F = 0.67$, $p = 0.647$, $\eta^2_G < 0.01$)

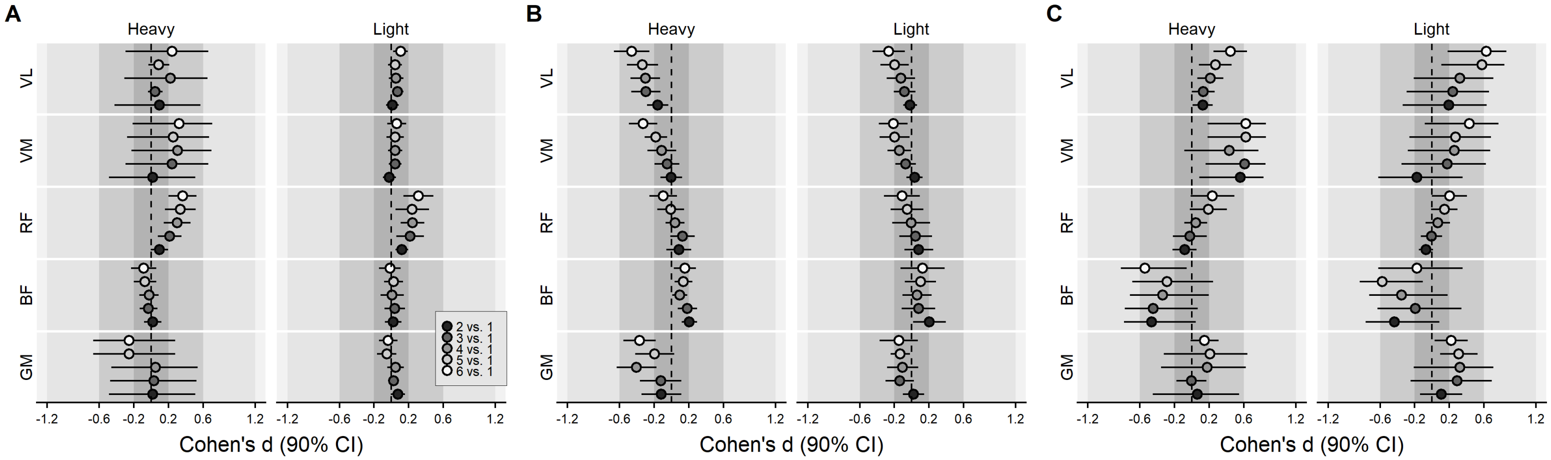

**Figure 3.22:** Standardized mean differences (Cohen's d) and confidence intervals (horizontal lines) in RMS (A), F med (B) and FI nsm5 (C) from the first repetition for each corresponding muscle (biceps femoris (BF), gastrocnemius medialis (GM), rectus femoris (RF), vastus lateralis (VL) and vastus medialis (VM)) and loading condition.

### 3.4.3 Discussion

The current study aimed to investigate the acute influence of moderate altitude exposure on maximal isometric strength and mechanical performance, muscle activation and perceived effort during a lower-body power-oriented resistance training session at two different loading conditions. The main findings revealed greater RPE values and decrements in movement velocity during the heavy condition at moderate altitude, although similar changes in the surface EMG signal occured in both altitude levels. On the contrary, greater impairments in mechanical performance, relative to the first repetition, were observed during the lighter training session in normoxia. Similar MVIF, and absolute CMJ mechanical performance were observed in both altitude levels. Similar increments in the interference EMG amplitude and $\mathrm{FI}_{\mathrm{nsm5}}$ and decrements in $\mathrm{F}_{\mathrm{med}}$ were observed across repetitions in RF, VL and VM muscles during both loading and altitude conditions.

The similar MVIF values observed at both altitude levels are in line with previous investigations reporting unchanged isometric strength of the ankle dorsiflexors (Garner et al. 1991), knee extensors (Fulco et al. 1996; Katayama et al. 2007) and hand muscles (Fulco et al. 1994; Szubski, Burtscher, and Löscher 2007). A few investigations have, nonetheless, reported greater isometric (Young et al. 1980) and dynamic (Feriche et al. 2014; García-Ramos, Štirn, et al. 2016) strength performance under moderate (Feriche et al. 2014; García-Ramos, Štirn, et al. 2016) and severe (Young et al. 1980) hypobaric hypoxia, although the evidence remains conflicting. While maximal dynamic strength (1RM) increased during the bench press exercise at moderate hypobaric hypoxia (Feriche et al. 2014), García-Ramos et al. (2016) observed improvements in the maximal theoretical velocity estimated from the FV relationship, but unchanged maximal strength levels during the loaded SJ exercise. On the contrary, Alhammoud et al. (2018) recently reported impaired rate of torque development, and unchanged MVIF, under acute normobaric hypoxic conditions ($\mathrm{FiO}_2 = 0.13$). While further research seems needed to address the potential differences between contraction and hypoxic modes, the current study explored in detail of how strength performance oscilates across repetitions and sets during training, which may provide a deeper insight into the influence of hypoxia.

Although greater power output was observed during the light loading conditions, in line with previous research (Cormie et al. 2007), performance decrements from the first repetition occurred at a slighlty higher rate during the heavier loading conditions (Figure 3.17), particularly at moderate altitude (Figure 3.19). On the contrary, the magnitude of performance loss relative to the first repetition was slightly greater under normoxic than hypoxic conditions during the light loading condition. These findings, mainly observed in the COM velocity changes (Figure 3.19), highlight the usefulness of monitoring movement velocity during resistance training (Sánchez-Medina and González-Badillo 2011; González-Badillo et al. 2017) and the potential interaction between loading and hypoxic modes during resistance training. Earlier investigations reporting greater performance fatibability under hypoxic conditions have been limited to intermittent (Fulco et al. 1994; Katayama et al. 2007; Millet et al. 2009) or sustanined (Eiken and Tesch 1984; Felici et al. 2001; Degens, Sanchez Horneros, and Hopman 2006)] isometric strength protocols. On the contrary, little evidence of greater performance fatigability has been reported during resistance training under normobaric hypoxic conditions. Scott and colleagues have repeatedly observed no significant influence of normobaric hypoxia on strength performance when performing back squats and deadlifts with heavy (Scott et al. 2015; Scott, Slattery, Sculley, Smith, et al. 2017) or moderate (Scott, Slattery, Sculley, and Dascombe 2017) loads. The ballistic nature of the CMJ exercise used in the current study, along with the greater influence of hypobaric hypoxia (Faiss et al. 2013), may be responsible for these results. In line with previous research (Brocherie, Millet, and Girard 2016), participants perceived harder the heavy training session when conducted at moderate altitude, while similar RPE values were observed during the light loading conditions. While these findings suggest a potential load-dependent influence of moderate altitude on performance fatigability, the similar changes observed in the interference EMG signal highlight the complex nature of fatigue development and our ability to assess it during resistance training. Further research may thus be needed on this regard.

In line with our results, increments in the amplitude of the EMG signal have been widely described during isolated muscle fatiguing isometric (Merletti, Lo Conte, and Orizio 1991) and dynamic (González-Izal, Malanda, et al. 2010) actions, although the influence of environmental hypoxia remains conflicting. While some studies have found greater increases in EMG amplitude during isometric (Katayama et al. 2007) and dynamic (Scott, Slattery, Sculley, Lockhart, et al. 2017) efforts under normobaric moderate hypoxic conditions, others have reported similar changes during both isometric (Alhammoud et al. 2018) and dynamic muscle efforts (Scott, Slattery, Sculley, Smith, et al. 2017; Lockhart et al. 2018). Although exercising under hypoxic conditions has been suggested to impact muscle fiber recruitment, the widely known limitations to infer motor unit behaviour from the interference EMG signal (Del Vecchio et al. 2017) encourage the use of new methodological advances (Glaser and Holobar 2018).

Despite the greater sensitivity of EMG spectral parameters to fatigue development (Dimitrov et al. 2006) and their link with relative changes in muscle conduction velocity (Stulen and De Luca 1978; Dimitrov et al. 2008), scarce research is available concerning the potential effects of resistance training under hypoxic conditions. Greater rates of change of spectral frequencies have been reported during sustained isometric efforts at high-altitude (Felici et al. 2001; Casale et al. 2004), although no other research has explored changes in the EMG signal spectral properties during resistance training exercises under normobaric or hypobaric hypoxic conditions. The results of the present study show similar changes in $F_{med}$ and $FI_{nsm5}$ across efforts in both altitude levels. Notwithstanding, considering the continuous (Felici et al. 2001) and isometric nature of previously used fatiguing protocols, meaningful differences may occur compared to dynamic and plyometric contractions. The higher levels of intramuscular pressure during isometric efforts (Sejersted et al. 1984) along with the task specificity of neuromuscular fatigue (Enoka and Duchateau 2016) may limit the direct comparison of findings from studies using isometric protocols to the applied experimental conditions employed in this experiment.

The ballistic nature of the movement used in this study, where participants were strongly encouraged to jump as high as possible in every repetition, may have particular consequences for muscle activation (Desmedt and Godaux 1977; Van Cutsem and Duchateau 2005) and fatigue (Komi 2000) development compared with isometric or non-ballisitc dynamic actions (Maluf et al. 2005; Dimitrov et al. 2006; González-Izal, Falla, et al. 2010). For example, Brandon et al. (2015) reported no significant changes in the EMG signal amplitude during a training session comprising explosive, but non-ballistic, squats at ~40% 1RM, which is a similar load than the one used in the heavy condition of our study. Other investigations have reported slighlty greater decrements in $F_{med}$ and increments in EMG amplitude during highly fatiguing protocols (i.e. 5 sets × 10 reps of legg press, 2 min rest; + 40% power output loss within sets) (González-Izal, Malanda, et al. 2010) compared to our power-oriented training protocol. Further research should extend the EMG spectral analysis to other resistance training protocols comprising higher levels of fatigue.

Interestingly, similar activation levels were observed in both loading conditions, in line with previous research (Giroux et al. 2015). Moreover, changes in the amplitude and spectral properties of the EMG signals were mainly observed on the knee extension muscles, which have been shown to be significantly involved during vertical jumping tasks (Rodacki, Fowler, and Bennett 2002; Giroux et al. 2015). While synergies between muscles could also have affected the interference EMG parametres examined here (Bobbert and van Ingen Schenau 1988), previous research suggests that muscle coordination during jumping is not affected by loading (Giroux et al. 2015) or fatiguing conditions (Rodacki, Fowler, and Bennett 2002), although the specific influence of resistance hypoxic training remains yet to be investigated.

In conclusion, the results of this study show that while no meaningful variations in MVIF or net mechanical performance during CMJ were observed at moderate altitude, greater perceived exertion and performance decrements across repetitions may occur during heavy, but not light loading conditions. Nonetheless, similar changes in the amplitude and spectral properties of the interference EMG signal (VL, VM, RF) were observed across repetitions during high (i.e. external load asociated with a mean propulsive velocity of 1.1 $m \cdot s^{-1}$) and light (i.e. 1.4 $m \cdot s^{-1}$) loading conditions in both altitudes explored.

## 3.5 Study 5: Intermittent resistance training at moderate altitude: effects on the force-velocity relationship, isometric strength and muscle architecture

### 3.5.1 Methods

#### Overview

A longitudinal repeated measures design was used to evaluate the functional and physiological muscle adaptations following resistance training at intermittent moderate altitude or normoxic conditions. One week before official testing, two familiarization sessions comprising loaded CMJ were carried out. Afterwards, participants attended the laboratory for three official testing sessions before (2-4 days pre-training) and after (2-4 days post-training) the 8-week training intervention. On days one and two, unilateral knee extension isometric force, voluntary muscle activation (surface electromyography [EMG]) and ultrasound-based muscle architecture repeated assessments were performed. Specific separate testing protocols were performed to measure maximal and explosive voluntary isometric force (Maffiuletti et al. 2016). In order to assess the between-day reliability of isometric and ultrasound measurements, assessments carried out on day one were repeated on a separate day. On the third visit to the laboratory (48 h later), participants first carried out a progressive loading FV test during the CMJ exercise and then performed a repeated jumping test consisting of fifteen continuous CMJ repetitions at maximum intended velocity. All laboratory assessments were performed under normoxic conditions (i.e. 690 m) and participants were asked to refrain from physical efforts, alcohol intake and maintain their sleep and diet habits 48 h before assessments. The training intervention comprised two continuous 4-week training periods (16 training sessions in total) of resistance training under normoxic environmental conditions (690 m; NT group) or intermittent terrestrial moderate altitude (at the High Performance Center of Sierra Nevada, 2320 m; IHRT group). Participants in the IHRT group travelled 32 Km by car to altitude to complete each training session and returned to normoxic conditions.

Arrivals and departures from altitude training took place ~20 min before and after the corresponding training session. The hypoxic environmental conditions during IHRT were ensured by assessing the arterial oxygen saturation ($SaO_2$) before each training session. Moreover, all participants were asked to avoid any lower-body resistance training activity out of the study.

### Participants

Twenty-seven physically active male Sport Science students (age: 22.5 ± 3.4 years, height: 177.0 ± 7.1 cm, body mass: 76.1 ± 8.5 kg) volunteered to participate in this study. All participants were informed regarding the nature, aims and risks associated with the experimental procedures and provided informed consent. Participants were familiarized with the resistance training exercises, although none of them was involved in systematic resistance training programme at the beginning of the study. None of them reported any physical limitations, health problems or musculoskeletal injuries that could compromise testing. Due to personal reasons, three participants withdrew from the study and twenty-four completed the training intervention (Hypoxia, n = 13 and Normoxia, n = 11). All participants were lowlanders and had not previously carried out any exercise training at altitude. All subjects gave written informed consent in accordance with the Declaration of Helsinki. The protocol was approved by the Granada University Ethic Committee.

### Testing procedures

### Training intervention

Training sessions were performed twice weekly, with at least a 48h rest between them. The training intervention consisted of two-consecutive 4-week resistance training periods. In order to optimize the power training adaptations (Cormie, Mcguigan, and Newton 2010), the first 4 weeks of training comprised bodyweight strength exercises, loaded squats and deadlifts and were designed to enhance general strength levels and CMJ jumping technique. During the back squat and deadlift exercises, the training load was individually set to ~12

RM. Two approximation sets (i.e. at 50% and 80% of their perceived 12 RM load) during the specific warm-up for each exercise were used to determine the individual training load for each session. This exercise program design was aiming to maximize muscle adaptations following lower-body explosive training (Haff and Nimphius 2012; Zamparo, Minetti, and di Prampero 2002). During the second 4-week training period, sessions were designed to improve both maximal power development and repeated jumping performance. A detailed description of the training program (i.e. exercises, sets, repetitions, rest periods, etc.) is shown in Table 3.8. All loaded CMJ were performed in a Smith Machine (Technogym, Gambettola, Italy) and the external load used was selected for every participant as the load associated with a barbell mean propulsive velocity of 1 $\mathrm{m{\cdot}s}^1$ (see below training load estimation procedure). Additionally, five minutes before the warm-up, the $SaO_2$ levels were measured using a pulse oximeter (Onyx Vantage 9590, Nonin, Plymouth, MN, USA). The IHRT group displayed a mean $SaO_2$ value of 93.6 ± 2.1 %.

**Table 3.8:** Training program description during the 8 weeks of training. All training sessions were preceded by a standardized warm-up protocol consisting of 5 min jogging and mobility exercises.

| Weeks 1-4 | | | | | | | | Weeks 5-8 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Sessions 1 and 3 | | Sessions 2 and 4 | | Sessions 5 and 7 | | Sessions 6 and 8 | | Sessions 9, 11, 13 and 15 | | Sessions 10, 12, 14 and 16 | |
| Exercise | Sets × reps (rest) | Exercise | Sets × reps (rest) | Exercise | Sets × reps (rest) | Exercise | Sets × reps (rest) | Exercise | Sets × reps (rest) | Exercise | Sets × reps (rest) |
| Jumping Jacks | 6 × 50 (1 min) | Rope jump | 6 × 50 (1 min) | Jumping Jacks | 3 × 50 (30 s) | Rope jump | 3 × 50 (30 s) | | | | |
| Air squat | 6 × 25 (1 min) | Step-up[c] | 6 × 20 (1 min) | Box jumps[c] | 5 × 10 (3 min) | Drop jumps[c] | 5 × 10 (3 min) | Jumping Jacks | 3 × 20 (30 s) | Jumping Jacks | 3 × 20 (30 s) |
| Back Squat[a] | 3 × 10 (2 min) | Back Squat[a] | 3 × 10 (2 min) | CMJ[d] | 5 × 10 (3 min) | Free barbell CMJ[a] | 5 × 10 (3 min) | Drop jumps[a] | 4 × 10 (4 min) | Loaded CMJ[b] | 5 × 6 (5 min) |
| Romanian Deadlift[a] | 3 × 10 (2 min) | Single-leg Deadlift[b] | 3 × 10 (1 min) | Romanian deadlift[a] | 3 × 10 (2 min) | Single-leg deadlift[ab] | 3 × 10 (1 min) | Loaded CMJ[b] | 5 × 6 (5 min) | Loaded CMJ[b] | 5 × 15 (3 min) |
| Sit-up | 5 × 20 (30 s) | Deadlift a[a] | 3 × 10 (2 min) | Sit-up | 5 × 20 (30 s) | Good-morning[b] | 3 × 10 (1 min) | Sit-up | 3 × 25 (30 s) | Back extension | 3 × 25 (30 s) |

[a] Training load (kg) approximated to 12 repetitions maximum and determined through 2 approximation sets

[b] Single-leg deadlifts load (kg) was 20 kg for all participants

[c] Step and box heights were 40 cm

[d] makecell[l]CMJs were performed with a free barbell. External load (kg) was 25% of each participant's body weight.

### Training load estimation

During the second 4-week period, the external load used during all loaded CMJ was estimated from the load-velocity relationship for each participant on a weekly basis. Precisely, during the 1st weekly training session, the load-velocity relationship was constructed by performing two CMJ attempts at three different absolute loading conditions (i.e. 20, 40, 60 kg). A linear regression model was fitted and used to estimate the external load corresponding to a barbell mean propulsive velocity of 1 $m \cdot s^{-1}$. This load is known to be equivalent to ~50-55% 1RM during the CMJ exercise. This procedure ensured that training loads were adjusted in both experimental conditions, and thus participants trained at the same relative intensity, for the same prescribed training volume.

### Data proccesing

### Knee extension isometric maximal and explosive strength

Maximal and explosive voluntary strength assessments were performed on a custom-made isometric rigid dynamometer (Maffiuletti et al. 2016) with knee and hip angles of 110 and 130 degrees (180 = full extension), respectively. Pelvis and shoulders were firmly secured to the chair and a rigid strap was attached proximally to the ankle (2 cm above the lateral malleolus) in series with a calibrated low-noise strain gauge (Force Logic, Swallowfield, UK). The force signal from the strain gauge was amplified (× 370) and digitized at 1 kHz using a 16-bit analog to digital converter (DT 9804; Data Translation, Marlboro, Massachusetts, USA). Following a standardized warm-up (three sustained contractions for 3-4 s at 20, 40, 60, and 80% of maximal perceived exertion), participants performed three maximal voluntary contractions (MVC) extending their knee "as hard as possible" for 3-5 s. Resting periods between efforts were set to 1 min. Thereafter, participants performed 10 explosive voluntary contractions interspersed by 30 s resting periods. They were instructed to push "fast, then strong" for ~1 second and to avoid any countermovement or pre-tension prior to the force onset. Force signals recorded from the strain gauge were filtered with a 4th order 150-Hz low pass Butterworth filter and were corrected for the influence of gravity during offline analysis. The highest instantaneous peak force achieved during the MVCs was defined as maximal voluntary force (MVIF). Force signals recorded during the explosive voluntary contractions were first analysed to determine onset and to discard any attempt with pre-tension or countermovement. Force onsets were automatically identified and visually confirmed (Tillin, Pain, and Folland 2013b), as the last zero-crossing point on the first derivative of the filtered signal force (de Ruiter et al. 2007). To discard any contraction with pre-tension or countermovement, 100 ms baseline force signals prior to force onset were fitted with a least-squares linear regression, and absolute slope values greater than 1.5 N·m·s$^1$ were set as a criterion for contraction omission due to potential effects of co-contraction or countermovement on explosive performance (de Ruiter et al. 2007). Explosive contractions reaching peak force $< 75\%$ MVIF were also discarded. From the remaining explosive voluntary contractions, the three attempts with the highest force at 100 ms were further analysed and eventually averaged across. For each contraction, force at 50 ms ($F_{50}$), 100 ms ($F_{100}$) and 150 ms ($F_{150}$) after the force onset were used for further analyses (Figure 3.23).

#### Surface electromyography (EMG)

During all isometric force assessments, EMG activity was recorded wirelessly from the vastus medialis (VM), vastus lateralis (VL) and rectus femoris (RF) muscles (Delsys, Boston, Massachusetts, USA). Raw EMG signals were amplified (×~1000) and sampled at 2 kHz. After skin preparation (shaving, light abrasion and cleaning with alcohol), EMG surface electrodes (Trigno Standard Sensor; Delsys Boston, Massachusetts, USA) were placed according to the surface EMG for non-invasive assessment of muscle recommendations (Hermens et al. 2000). EMG signals were first filtered with a 4th order band-pass Butterworth filter (6-450 Hz). The EMG signal during MVCs was assessed with a 500 ms root mean square (RMS) epoch, 250 ms either side of the peak EMG (Buckthorpe et al. 2012), averaged across muscles and taken as maximal EMG activation during MVC ($EMG_{MVC}$). During explosive contractions, EMG onset was manually identified as the first muscle to be activated. Specifically, raw EMG signals were graphically displayed with systematic x and y-axis (i.e. 300 ms and ± 0.05 mV, respectively) before manually selecting the last point at which the signal deflected away

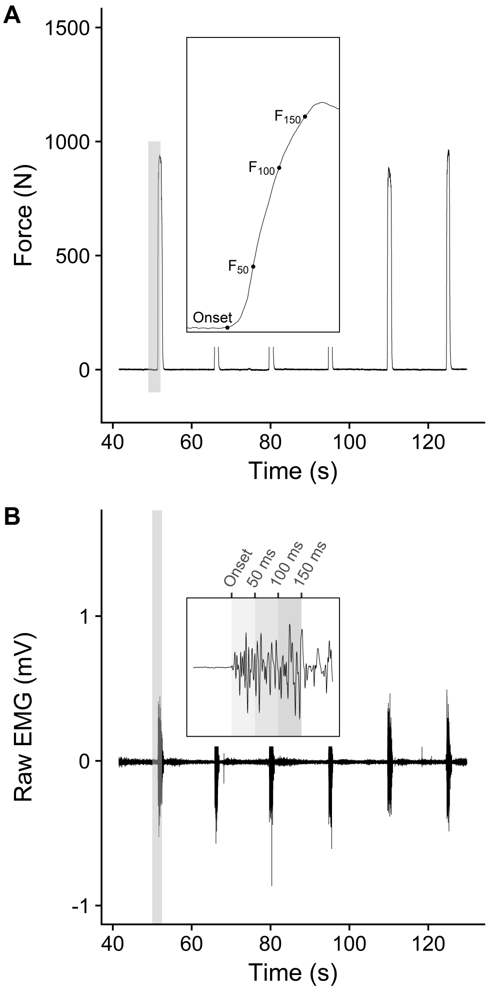

**Figure 3.23:** (A) Typical example of force trace during an isometric explosive strength assessment. Each contraction onset was automatically detected as the as the last zero-crossing point on the first derivative of the filtered signal force (de Ruiter et al., 2007), and force values at 50, 100 and 150 ms were compared. (B) Typical example of EMG recording during the isometric contractions. Signal onset was manually identified and the root means square (RMS) was averaged across 0-50 ms, 50-100 ms and 100-150 ms time periods after onset.

from baseline (Balshaw et al. 2016). Thereafter, RMS EMG was averaged over three periods from the EMG onset: 0-50 ms, 50-100 ms and 100-150 ms ($EMG_{0\text{-}50}$, $EMG_{50\text{-}100}$, $EMG_{100\text{-}150}$, respectively), normalised to $EMG_{MVIF}$ and averaged across muscles (Figure 3.23).

### Muscle architecture

Figure 3.24 shows an overview of the muscle architecture measurements carried out. For each measurement site, muscle thickness was measured as the perpendicular distance between superficial and deep aponeuroses, averaged at three evenly spaced points along the image width (i.e. two at the edges, one at midpoint). Pennation angle was measured along the VL muscle (i.e. at 20, 50 and 60% of thigh length), as the angle between the deep aponeurosis and the line of the fascicle. Moreover, VL fascicle length (FL) was estimated as (Equation (3.11)):

$$FL = \frac{Thickness}{sin\ \theta} \tag{3.11}$$

where $\theta$ is the fascicle pennation angle. Three pennation angle and FL measurements were performed on the two repeated images for each measurement site, and an average was taken to provide overall VL pennation angle and FL.

### Countermovement-jump incremental test

After a standardized warm-up protocol (i.e. 5 min jogging, joint mobility exercises and five unloaded CMJ), participants completed an incremental CMJ test at five absolute loading conditions (i.e. 17, 30, 45, 60 and 75 kg) using a Smith Machine (Technogym, Gambettola, Italy). Two attempts were performed at each loading condition and resting time between repetitions and loads was set to 1 and 3 min, respectively. Instructions to keep constant downward pressure on the barbell and to jump as high as possible were given. Also, participants were instructed to perform a CMJ depth of ~90 degree of knee flexion to keep it constant across the different loading conditions. All jumps were performed on a force plate (Type 9260AA6, Kistler, Switzerland) which recorded vertical ground reaction force (GRF)

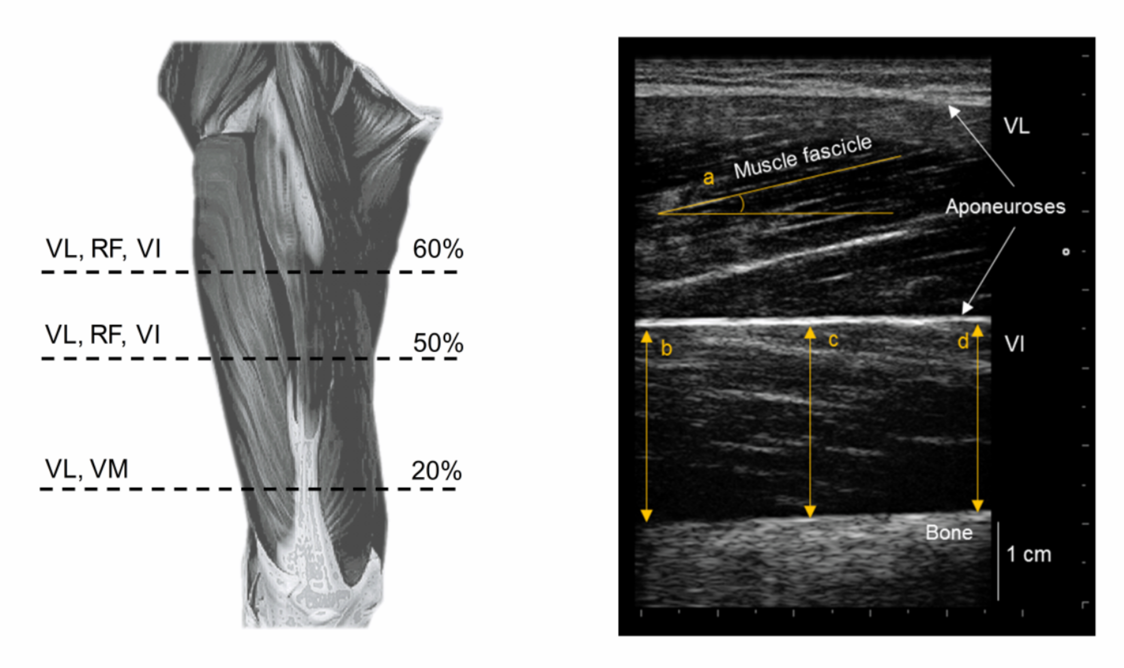

**Figure 3.24:** (A) Muscle architecture assessments. Muscle thickness measurements on vastus lateralis (VL), rectus femoris (RF), vastus medialis (VM) and vastus intermedius (VI) were performed at each corresponding measurement location (% thigh length). Muscle thickness VI measurements were performed in the anterior portion, in the same location as RF measurements. Pennation angles and linear estimations of fascicle lengths were averaged across the three VL muscle measurements.

data at 1 kHz, using an analog-to-digital converter (DAQ system 5691A1, Kistler). Signals were collected through the BioWare software (Kistler, Winterthur, Switzerland). For each jump, the system centre of mass (COM) velocity was calculated from vertical GRF recordings (Linthorne 2001). Specifically, net GRF was calculated by subtracting the system weight and then divided by the system mass (kg) to provide acceleration. Acceleration was numerically integrated to provide instantaneous COM velocity. Further analyses were performed on the concentric movement phase, defined from the onset of upward motion (i.e. instantaneous COM velocity $>$ 0 m·s-1) to the take-off instant (i.e. GRF $<$ 5 N). Only the repetition with the highest mean velocity and correct COM displacement was selected for further analysis. At each loading condition, mean power output was obtained and used for comparisons. Moreover, force and velocity were averaged across the concentric phase of each load and modelled by a least-squares linear regression model to calculate the FV profile variables. The intercepts of the FV relationship with the force and velocity axes were taken to calculate the maximal theoretical force (i.e. force value when velocity is 0; $\mathrm{F}_0$) and maximal theoretical velocity (i.e. velocity when force is 0; $\mathrm{V}_0$), respectively. The slope of the relationship ($\frac{F_0}{V_0}$) and maximal theoretical power ($\mathrm{P}_0$) (computed as $P_0 = \frac{F_0 \cdot V_0}{4}$) were also analysed.

### Repeated countermovement jump test

Fifteen minutes after the completion of the FV incremental test, participants carried out a 15-repetition CMJ test at maximum intended velocity (Nindl et al. 2002). For each participant, the external load used during the test was individually selected as the load associated with barbell mean propulsive velocity of 1 $\mathrm{m \cdot s^{-1}}$, interpolated from the load-velocity relationship performed on that day. All repetitions were performed continuously, and participants were verbally encouraged to jump as high as possible and to maintain CMJ depth constant during all repetitions. A linear velocity transducer (T-Force System; Ergotech, Murcia, Spain) providing barbell displacement instantaneous feedback was used to calculate mean propulsive power for each repetition. The mean propulsive power averaged across all 15 CMJ repetitions were measured and used for further comparisons ($\mathrm{CMJ}_{15\mathrm{MP}}$).

All signal data analyses were performed using custom-written scripts computed with MAT-

LAB (version R2015a; The Mathworks, Natick, Massachusetts, USA).

### Statistical Analysis

Descriptive statistics are presented as mean ± standard deviation (SD). Normal distributions of the data were confirmed using a Shapiro-Wilk test. Between-day reliability of isometric torque, ultrasound and EMG parameters was assessed by calculating the intraclass correlation coefficient (ICC), coefficient of variation (CV) and corresponding 95% confidence intervals. Separate two-factor mixed ANOVAs were used to assess the effects of time (within-participant factor: pre vs. post) and training group (between-participants factor: IHRT vs. NT) on the FV-profile variables (i.e. $F_0$, $V_0$, $P_0$, Slope), $CMJ_{15MP}$, MVIF, $EMG_{MVC}$ and VL pennation angle and fascicle length. A three-factor mixed analysis of variance (ANOVA) was used to evaluate the effects of training group (between-participants factor: IHRT vs. NT), time (within-participant factor: pre vs. post) and loading condition (within-participant factor: 17, 30, 45, 60 and 75 kg) on power output. Separate three-factor mixed ANOVAs were employed to evaluate the effects of training group (between-participants factor: IHRT vs. NT), time (within-participant factor: pre vs. post) and contraction timing (i.e. $F_{50}$, $F_{100}$, $F_{150}$ and $EMG_{0\text{-}50}$, $EMG_{50\text{-}100}$ and $EMG_{100\text{-}150}$, in the isometric force and EMG variables, respectively) on explosive strength and EMG activation variables. Finally, a three-factor mixed ANOVA was also used to assess the effects of training group (between-participants factor: IHRT vs. NT), time (within-participant factor: pre vs. post) and muscle site (eight level within-participant factor: VL, RF, VI and VM muscles at each corresponding thigh length: 20%, 50% and 60%). Alpha was set at 0.05 for ANOVAs. Generalized Eta-Squared measures of effect size and thresholds (0.02 [small], 0.13 [medium] and 0.26 [large]) were calculated along with ANOVA effects (Bakeman 2005).

In addition to the null-hypothesis statistical testing, standardized differences (i.e. Cohen's d effect sizes; thresholds: >0.2 [small], >0.6 [moderate], >1.2 [large] and very large [>2]; [Hopkins et al., 2009]) with 90% confidence intervals and qualitative probabilistic inferences indicating confidence (*possibly*, *likely*, *most likely*, *almost certainly*) and magnitude levels of the observed changes (trivial, small, moderate, large, very large) were calculated. All statistical analyses were performed using R software (version 3.3.2, The R Foundation for Statistical Computing, 2016). Packages 'ez' (Lawrence 2016) and 'mbir' (Peterson 2017) were employed to perform ANOVA and magnitude-based inferences, respectively.

### 3.5.2 Results

#### Reliability of isometric and muscle architecture measurements

Reliability data on the isometric strength, voluntary activation and muscle architecture variables is shown in Table 3.9.

**Table 3.9:** Reliability outcomes of isometric strength (N), electromyography ($EMG_{0-50}$, $EMG_{50-100}$ and $EMG_{100-150}$ [% $\mathrm{MVC_{EMG}}$]; $\mathrm{EMG_{MVC}}$ [mV]) and muscle architecture (RF, VI, VL and VM muscles thickness at 20, 50 or 60% of thigh length [mm]; pennation angle [deg] and fascicle length [mm]) variables measured from the two repeated measurements prior to the training intervention.

| | Test 1 (Mean ± SD) | Test 2 (Mean ± SD) | CV % (95% CI) | ICC (95% CI) |
|---|---|---|---|---|
| **Isometric Strength** | | | | |
| MVIF | 890.0 ± 187.3 | 883.2 ± 181.4 | 3.76 (2.3, 5.22) | 0.97 (0.93, 0.99) |
| $F_{50}$ | 151.4 ± 70.3 | 176.0 ± 52.6 | 24.71 (14.21, 35.21) | 0.68 (0.2, 0.87) |
| $F_{100}$ | 459.4 ± 145.8 | 481.6 ± 101.1 | 11.39 (5.12, 17.66) | 0.86 (0.66, 0.94) |
| $F_{150}$ | 621.1 ± 175.3 | 631.1 ± 134.0 | 8.69 (4.01, 13.36) | 0.90 (0.75, 0.96) |
| **Electromyography** | | | | |
| $EMG_{0-50}$ | 60.3 ± 26.6 | 68.2 ± 18.7 | 23.5 (12.62, 34.38) | 0.52 (-0.18, 0.81) |
| $EMG_{50-100}$ | 87.6 ± 25.6 | 95.1 ± 21.4 | 17.3 (11.17, 23.43) | 0.45 (-0.35, 0.78) |
| $EMG_{100-150}$ | 77.8 ± 18.8 | 83.1 ± 18.6 | 14.3 (8.86, 19.74) | 0.56 (-0.08, 0.82) |
| $EMG_{MVC}$ | 0.23 ± 0.10 | 0.25 ± 0.12 | 9.44 (6.03, 12.86) | 0.97 (0.93, 0.99) |
| **Muscle arquitecture** | | | | |
| $RF_{50}$ | 23.8 ± 2.9 | 23.6 ± 2.9 | 2.3 (1.13, 3.48) | 0.96 (0.9, 0.98) |
| $RF_{60}$ | 25.3 ± 2.5 | 24.7 ± 2.8 | 3.27 (2.13, 4.41) | 0.93 (0.82, 0.97) |
| $VI_{50}$ | 21.5 ± 4.1 | 21.5 ± 4.3 | 3.15 (2.02, 4.28) | 0.98 (0.95, 0.99) |
| $VI_{50}$ | 22.2 ± 4.5 | 22.3 ± 5.1 | 4.02 (2.1, 5.93) | 0.96 (0.91, 0.98) |
| $VL_{20}$ | 17.4 ± 5.7 | 17.9 ± 4.7 | 8.81 (3.59, 14.02) | 0.93 (0.83, 0.97) |
| $VL_{50}$ | 25.7 ± 2.6 | 25.8 ± 2.9 | 2.72 (1.75, 3.68) | 0.95 (0.87, 0.98) |
| $VL_{60}$ | 27.7 ± 2.9 | 26.9 ± 2.8 | 2.92 (1.64, 4.2) | 0.93 (0.84, 0.97) |
| $VM_{20}$ | 20.7 ± 4.7 | 20.9 ± 5.1 | 6.36 (3.65, 9.07) | 0.94 (0.85, 0.98) |
| VL p angle | 11.7 ± 1.7 | 12.5 ± 1.4 | 6.99 (4.65, 9.33) | 0.84 (0.61, 0.94) |
| VL f length | 124.2 ± 22.3 | 113.3 ± 18.9 | 8.33 (5.36, 11.31) | 0.83 (0.61, 0.93) |

### Muscle architecture

Muscle thickness values for each corresponding training group are shown in 3.25. ANOVA showed a main effect of muscle site ($F = 38.00$, p $< 0.001$, $\eta^2_G = 0.43$), and a time × muscle site interaction effect ($F = 10.85$, p $< 0.001$, $\eta^2_G = 0.02$) on muscle thickness, due to small increments in $\mathrm{VL_{50}}$, VI and VM muscles (3.25). No main effect of time ($F = 3.36$, $p = 0.080$,

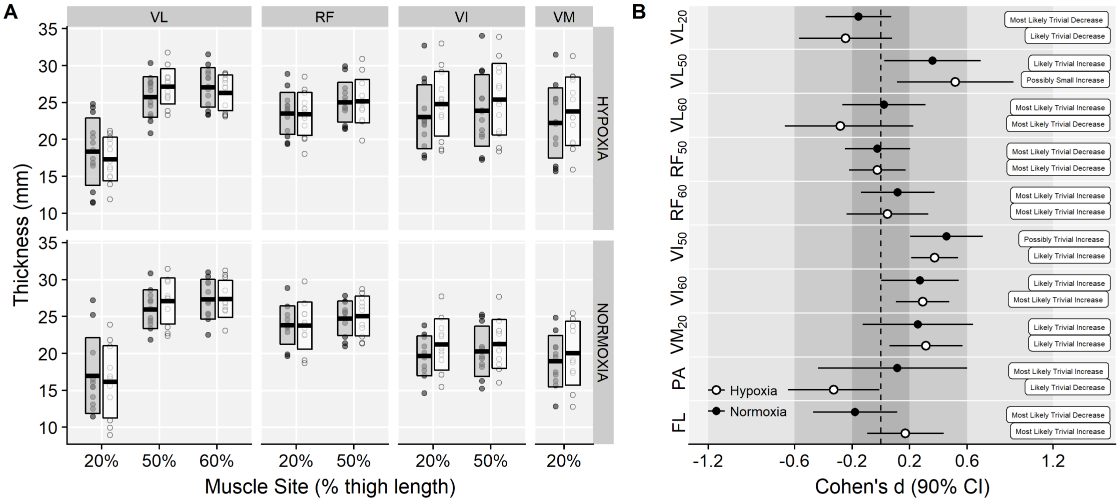

**Figure 3.25:** (A) Muscle thickness raw values for each corresponding muscle location before (grey-filled boxes) and after (white boxes) training. Horizontal thick lines within bars are mean and upper and lower bars edges define standard deviation. Individual observations are shown as grey or white circles, respectively. (B) Cohen's d standardized mean differences with 90% confidence intervals and magnitude-based inferences for the muscle architecture variables.

$\eta^2_G < 0.01$), training group × time ($F = 0.01$, $p = 0.939$, $\eta^2_G < 0.01$) or training group × time × muscle site interaction effects were observed on muscle thickness ($F = 0.56$, $p = 0.722$, $\eta^2_G$ $< 0.01$). No main effects of time (12.1 ± 1.4 vs. 11.9 ± 1.3 °, pre to post training respectively; $F = 0.29$, $p = 0.596$, $\eta^2_G < 0.01$) or training group ($F = 0.03$, $p = 0.871$, $\eta^2_G < 0.01$) were observed on VL pennation angle. A small training group × time effect was observed ($F =$ $3.06$, $p = 0.094$, $\eta^2_G = 0.02$) due to small decrements in the IHRT group (12.3 ± 1.3 vs. 11.8 ± 1.3 ° and 11.8 ± 1.6 vs. 12.1 ± 1.4 °, in the IHRT and NT groups, respectively; Figure 3.25). Similarly, no main effects of time ($F = 0.07$, $p = 0.790$, $\eta^2_G < 0.01$) and a trivial training group × time interaction effect (115.2 ± 16.8 vs. 118.2 ± 16.2 mm and 120.5 ± 22.2 vs. 116.3 ± 21.4 mm, in the IHRT and NT groups, respectively; $F = 2.57$, $p = 0.123$, $\eta^2_G <$ $0.01$) were observed on fascicle length (Figure 3.25).

### Isometric force

There was a main effect of time on MVIF ($F = 29.96$, p $< 0.001$, $\eta^2_G = 0.06$) due to increments in both experimental groups. No main effect of training group ($F = 2.89$, $p = 0.104$, $\eta^2_G =$ $0.12$) or time × training group interaction ($F = 0.22$, $p = 0.645$, $\eta^2_G < 0.01$) were observed on MVIF (Figure 3.26). Likewise, no main effects of time ($F = 0.04$, $p = 0.853$, $\eta_G^2 < 0.01$) or time × training group interaction effects ($F = 0.25$, $p = 0.620$, $\eta_G^2 < 0.01$) were observed on the explosive isometric strength (Figure 3.26).

### Electromyography (EMG)

No main effects of time ($F = 0.64$, $p = 0.432$, $\eta_G^2 < 0.01$) or training group ($F = 0.17$, $p = 0.686$, $\eta_G^2 < 0.01$) were found on $\mathrm{EMG_{MVC}}$. Likewise, there was no training group × time interaction effect (0.22 ± 0.07 vs. 0.23 ± 0.08 mV in the IHRT group and 0.24 ± 0.15 vs. 0.25 ± 0.13 mV in the NT group, pre to post training, respectively; $F = 0.00$, $p = 0.952$, $\eta_G^2 < 0.01$). ANOVA showed no main effects of time ($F = 0.04$, $p = 0.853$, $\eta_G^2 < 0.01$) or time × training group interaction effect on the EMG activation during the explosive contractions ($F = 0.25$, $p = 0.620$, $\eta_G^2 < 0.01$; Figure 3.26).

### Force-velocity test

Main effects of time ($F = 30.91$, $p < 0.001$, $\eta_G^2 = 0.10$) and loading condition ($F = 34.18$, $p < 0.001$, $\eta_G^2 = 0.07$) were observed on power output. However, no meaningful training group × time ($F = 0.22$, $p = 0.647$, $\eta_G^2 < 0.01$), time × load ($F = 1.97$, $p = 0.132$, $\eta_G^2 < 0.01$), training group × load ($F = 0.08$, $p = 0.932$, $\eta_G^2 < 0.01$) or training group × load × time ($F = 1.89$, $p = 0.145$, $\eta_G^2 < 0.01$) interaction effects were observed (Figure 3.27).

Regarding the FV profile parameters, significant main effects of time were observed on $F_0$ (35.6 ± 5.4 vs. 38.5 ± 5.4 $\mathrm{N{\cdot}kg^{-1}}$; $F = 6.55$, $p = 0.018$, $\eta_G^2 = 0.07$) and $P_0$ (29.8 ± 4.1 vs. 31.5 ± 5.0 $\mathrm{W{\cdot}kg^{-1}}$; $F = 6.45$, $p = 0.019$, $\eta_G^2 = 0.04$). There was a main effect of training group on $P_0$ ($F = 4.94$, $p = 0.037$, $\eta_G^2 = 0.17$) due to greater values in the IHRT compared to the NT group (32.4 ± 3.2 vs. 28.7 ± 4.6 $\mathrm{W{\cdot}kg^{-1}}$). No main effects of time on $V_0$ (3.38 ± 0.51 vs. 3.30 ± 0.54 $\mathrm{m{\cdot}s^{-1}}$; $F = 0.43$, $p = 0.521$, $\eta_G^2 < 0.01$), Slope (-10.9 ± 2.9 vs. -12.1 ± 3.0 $\mathrm{N{\cdot}s{\cdot}m^{-1}{\cdot}kg^{-1}}$; $F = 2.19$, $p = 0.153$, $\eta_G^2 = 0.04$) or time × training group interactions were observed on any of the FV profile variables ($F_0$: $F = 0.33$, $p = 0.569$, $\eta_G^2 < 0.01$; $V_0$: $F =$

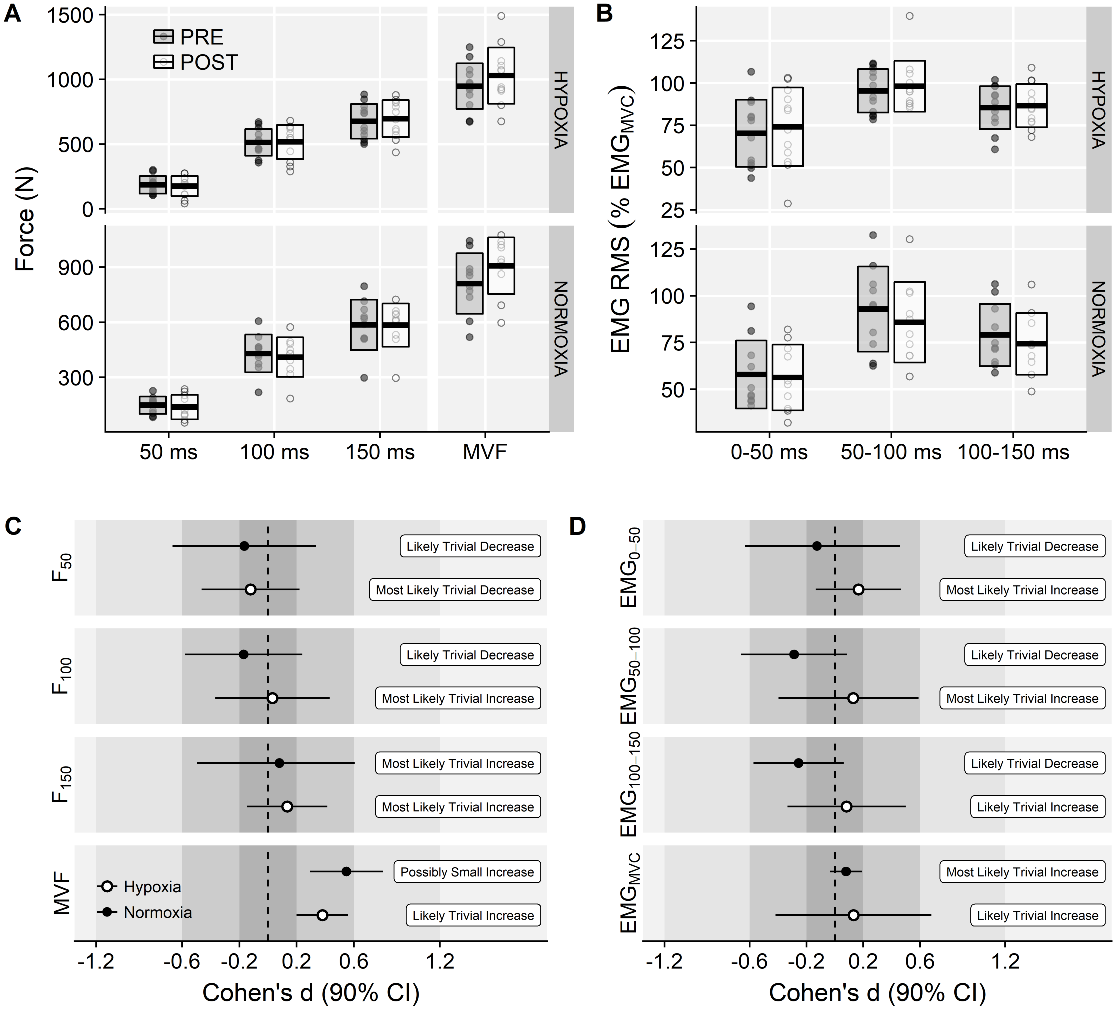

**Figure 3.26:** (A) Isometric explosive and maximal force values before and after the training intervention at each corresponding environmental condition. (B) Voluntary activation levels (EMG RMS normalized to EMGMVC) before and after the training intervention. In top panels, horizontal thick lines within bars are mean and upper and lower bars edges define standard deviation. Individual observations are shown as grey or white circles, respectively. Both (C) and (D) panels display magnitude-based inferences for the isometric strength and EMG activation variables.

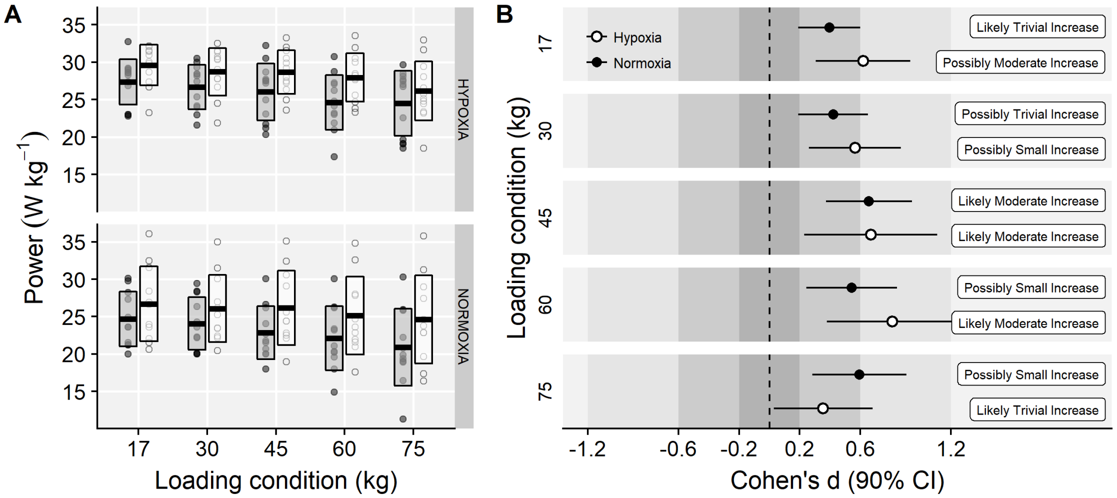

**Figure 3.27:** (A) Power output values at each loading condition before (grey-filled boxes) and following (white boxes) training. Horizontal thick lines within bars are mean and upper and lower bars edges define standard deviation. Individual observations are shown as grey or white circles, respectively. (B) Cohen's d standardized mean differences and 90% confidence intervals for each corresponding variable.

1.33, $p = 0.261$, $\eta^2_G = 0.03$; $P_0$: $F = 1.04$, $p = 0.320$, $\eta^2_G < 0.01$; Slope: $F = 0.39$, $p = 0.541$, $\eta^2_G < 0.01$; Figure 3.28).

#### Repeated CMJ test (CMJ$_{15MP}$)

ANOVA showed a main effect of time on CMJ$_{15MP}$ (9.5 ± 1.8 vs. 10.3 ± 2.1 W·kg$^1$; $F = 16.15$, p $< 0.001$, $\eta^2_G = 0.04$). A small main effect of training group was observed ($F = 3.81$, $p = 0.064$, $\eta^2_G = 0.15$), although no meaningful time × training group interaction effects were observed ($F = 0.18$, $p = 0.679$, $\eta^2_G < 0.01$; Figure 3.29).

### 3.5.3 Discussion

The present study examined the effects of an 8-week resistance training intervention, under normoxic or moderate altitude environmental conditions (i.e. intermittent exposure), on the functional (i.e. maximal and explosive strength performance), voluntary EMG activation and morphological adaptations of the quadriceps muscles. The main results, specific to the training strategy employed, showed similar functional and morphological training muscle

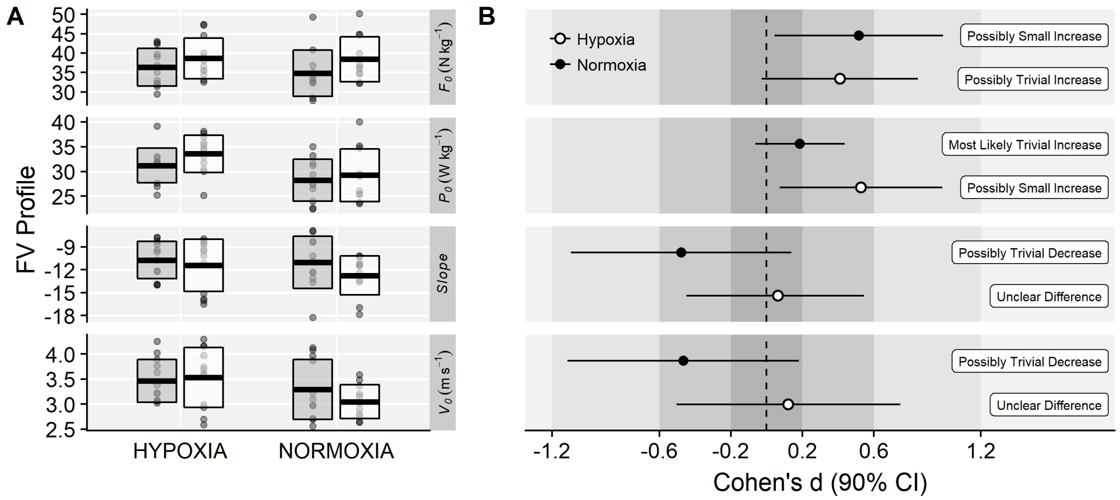

**Figure 3.28:** (A) Raw values of the FV profile related variables before (grey-filled boxes) and after (white boxes) training. Slope units are N·s·m$^{-1}$·kg$^{-1}$. Horizontal thick lines within bars are mean and upper and lower bars edges define standard deviation. Individual observations are shown as grey or white circles, respectively. (B) Cohen's d standardized mean differences and 90% confidence intervals for each corresponding variable.

responses in both environmental conditions. Despite no meaningful between-group statistical differences, opposite trends in pennation and fascicle length changes were depicted.

Compared to NT, the IHRT intervention exhibited similar maximal strength responses assessed either from the FV-relationship (i.e. $F_0$) or using a single-leg knee extension isometric MVC. These results contribute to the conflicting IHRT research available showing significant (Inness et al. 2016; Yan et al. 2016) and non-meaningful changes in maximal strength compared to training under normoxic conditions (Ho et al. 2014; Kurobe et al. 2015). The wide variety of training protocols and strength assessment procedures used in previous research (i.e. dynamic: direct (Inness et al. 2016) and indirect (Nishimura et al. 2010) estimations of 1RM; static: bilateral (Yan et al. 2016) and unilateral (A. Manimmanakorn, Hamlin, et al. 2013) isometric MVIF) make direct comparisons difficult. Strength training responses are known to be load and task-specific (Cormie, McGuigan, and Newton 2010), which may partially explain the conflicting evidence often reported in the current IHRT literature. The five-load FV-profile assessment procedure used in this investigation shows that training adaptations were maximized in the loading conditions close to the training load used (i.e. greatest changes in power output in 60 kg), although no meaningful differences between loading conditions were observed. Indeed, while "small" to "moderate" changes in both $F_0$ and MVIF

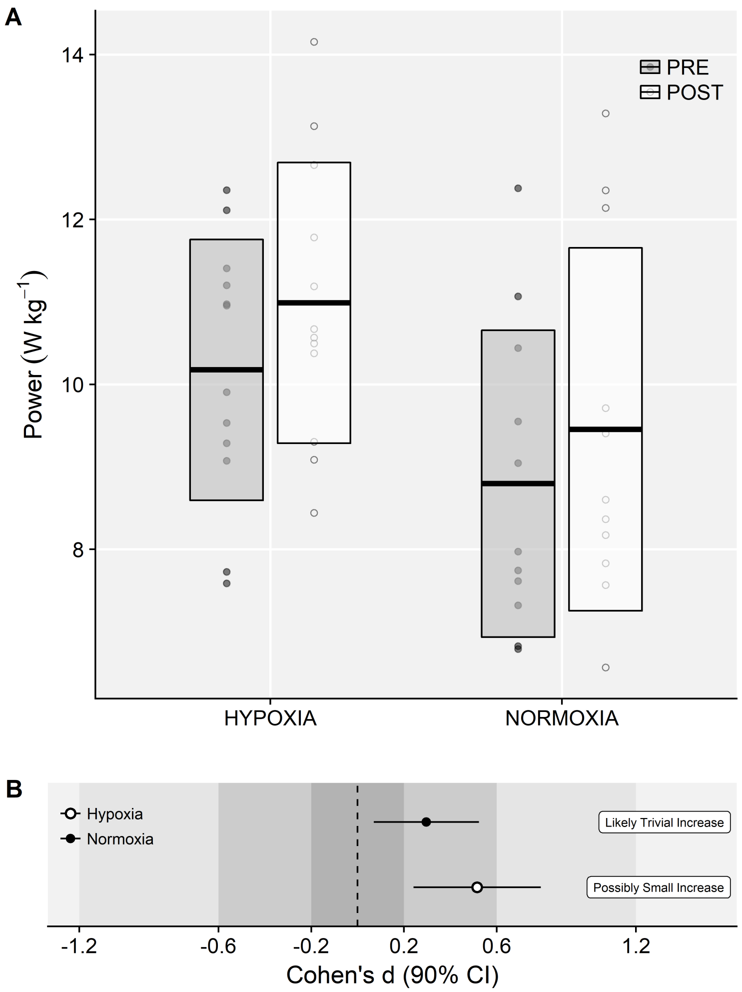

**Figure 3.29:** (A) Mean power values obtained during the repeated CMJs test ($\mathrm{CMJ}_{15\mathrm{MP}}$). Horizontal thick lines within bars are mean and upper and lower bars edges define standard deviation. Individual observations are shown as grey or white circles, respectively. (B) Cohen's d standardized mean differences and 90% confidence intervals for each corresponding variable.

occurred in both groups, unclear changes in $V_0$ and unchanged isometric explosive performance were observed. Consequently, "small" changes in the overall FV-performance (i.e. $P_0$) were observed only in the IHRT group, although group differences with NT were trivial. It should be noted that these responses are consistent with the training load adjustment approach used. The fact that training velocity was kept at 1 $m \cdot s^{-1}$ and thus the training load increased throughout the training period likely explains why changes in maximal but no explosive strength parameters (i.e. $F_{50}$, $F_{100}$, $F_{150}$, $V_0$) were observed in both groups.

Neuromuscular and muscle morphological changes are known to underpin changes in muscle strength following resistance training (Folland and Williams 2007). The use of IHRT to maximize muscle growth remains one of the potential training applications (Deldicque and Francaux 2013; A. Manimmanakorn, Hamlin, et al. 2013; Nishimura et al. 2010) even in the absence of muscle functional adaptations (Kurobe et al. 2015). In the present study, however, no differences between training conditions were observed on the muscle thickness changes. Both groups showed region-specific morphological changes, with "small" changes in the thickness of VL and VI muscles (see Figure **??**). The small magnitude of the observed muscle thickness changes after both IHRT and NT is likely explained by the high-intensity, power-oriented (Blazevich et al. 2003) and short-term nature of the training intervention employed (Blazevich et al. 2007). Despite unclear differences between groups, a tendency towards smaller VL pennation angles and greater fascicle lengths in the IHRT group was observed, which has been previously linked with velocity-specific muscle architecture responses (Blazevich et al. 2003). Variations in the amount of skeletal muscle contractile tissue are known to underpin changes in muscle architecture (Blazevich and Sharp 2005; Narici, Franchi, and Maganaris 2016). However, while training-specific changes in muscle architecture could be expected, neither the training period length nor the sets and repetitions schemes employed in the current investigation were designed to specifically target skeletal muscle growth (Schoenfeld et al. 2017). Instead, a combination of neuromuscular and structural changes of the muscle-tendon unit is known to determine muscle power production (Cormie, McGuigan, and Newton 2011b), which are likely to account for the improvements in strength performance observed here. Notwithstanding, no significant changes in voluntary activation were observed during isometric maximal and explosive strength assessments. Task-specific adaptations (Buckthorpe et al. 2015), as well as the high between-day variability observed in the EMG variables, may explain the lack of neural effects observed in muscle activation.

It should be considered that the current experimental design did not comprise a mid-intervention assessment, which would have allowed to examine potential differences in the time course of training-induced responses. While neural adaptations are thought to be responsible for the early responses to resistance training (Folland and Williams 2007; Moritani and deVries 1979), other biomechanical factors not comprised in the current investigation, should have been also considered to reach a comprehensive evaluation of the mechanisms determining muscle performance. Task-specific neuromuscular adaptations (i.e. changes in muscle coordination) and changes in the mechanical properties of the muscle-tendon unit may have occurred and should be addressed in future investigations.

Collectively, the results of the present investigation display similar responses in terms of muscle strength and muscle architectural adaptations following an 8-week resistance training intervention. Nonetheless, these and previous findings suggest that, contrary to earlier adverse associations between altitude and resistance-training muscle responses (Narici and Kayser 1995), similar anatomical and functional muscle strength responses can be achieved in both environmental conditions. Interestingly, these results may be of relevance for athletes and coaches planning their altitude training strategies.

# Chapter 4

# General discussion and conclusions

The aim of this thesis was to explore the influence of intermittent exposure to moderate altitude on the acute and short-term functional and physiological adjustements to power-training. Accordingly, the set of experiments conducted have helped to improve our understanding of several methodological and experimental questions concerning the topic of resistance hypoxic training. Two main investigations were carried out to 1) explore the influence of acute moderate altitude exposure on squat MVIF and changes in the lower-body mechanical performance and muscle activation during a power-oriented training session (Chapter 3.4) and 2) investigate the short-term adaptive responses following an 8-week IHRT strategy (Chapter 3.5). Other precedent experimental work allowed to refine the methodological procedures employed concerning the assessment of muscle strength (Experiment 3.3), training monitoring and responses (Experiment 3.1) and the analisis of the EMG signal during CMJ-based resistance training (Experiment 3.2).

Experiment 3.4 showed that while MVIF and absolute mechanical performance during CMJ remained unchanged at moderate altitude, greater perceived exertion and load-specific performance fatigability effects may occur during power-oriented resistance training. Previous research has suggested greater myoelectric fatigue symptoms from the surface EMG signal during isometric efforts performed under severe hypobaric (Felici et al. 2001) and normobaric (Katayama et al. 2007) hypoxic conditions. However, these results displayed similar changes in the amplitude and spectral properties of the interference EMG signal (VL, VM, RF) across repetitions in both altitude levels. These findings highlight the complex nature of performance fatigability (Enoka and Duchateau 2016; Thomas, Goodall, and Howatson 2018), with both central and peripheral components of the nervous system interacting in a task-specific manner. This investigation comprised a comprehensive analysis of the interference EMG signal, first developed in Experiment 3.2 and technically detailed in Appendix 6, providing detailed information about the muscle EMG changes occuring during a lower-body loaded CMJ training protocol, in both altitude conditions. The results extend previous work on the field describing changes in EMG amplitude during resistance hypoxic training (Lockhart et al. 2018). Furthermore, in line with precedent research, the results of this investigation highlight the potential use of monitoring movement velocity during resistance training (González-Badillo et al. 2017; González-Badillo and Sánchez-Medina 2010).

The adaptive responses to eight weeks of IHRT under moderate hypobaric conditions, at a functional and neuromuscular level, were then explored in Experiment 3.5. Overall, similar changes in strength, muscle structure and quadriceps activation during explosive isometric contractions were observed in both experimental groups. Notwithstanding, small changes in the overal force-velocity performance (i.e. $P_0$) were only observed in the IHRT group (see Figure 3.28), although group differences with the normoxic training were trivial. A velocity-based resistance training approach was also employed, ensuring the weekly adjustement of training loads in both experimental groups, without the need for maximal 1RM assessment. Moreover, this intervention comprised a periodized training approach to maximize the adaptations during the power-oriented training phase. The use of both static and dynamic strength measurements, provided evidence for the training-specific adative response widely observed in other investigations (Cormie, McGuigan, and Newton 2010; Buckthorpe et al. 2015). While meaningful changes in power output were observed in both experimental groups, no changes were detected in explosive isometric performance assessed during the unilateral knee-extension assessment task. As discussed in Experiment 3.3, the high variability often reported in early phase explosive performance (Maffiuletti et al. 2016) as well as the contraction and movement specificities (Tillin, Pain, and Folland 2018) may explain these results and encourage the use of similar training and testing procedures.

These investigations suggest that while moderate altitude may affect the perceptual and performance fatigability responses during CMJ training, comparable anatomical and functional muscle strength adaptations seem to occur in both environmental conditions. Despite the similar responses observed between environmental conditions, it should be reminded that these results apply to the intermittent hypoxic strategy employed, in an active, but non-elite population. It should be also kept in mind that the experimental conditions employed here significantly differ from most high-altitude expedition studies. Differences in physical activity, nutrition and the hypoxic doses should be particularly interpreted in each case when evaluating the influence of altitude exposure on muscle strength performance.

The applied experimental approach carried out in this thesis may comprise both positive and and negative aspects. On the one hand, these findings remain as close as possible to the real life movement and muscle functioning strength training situations to which athletes are exposed daily. On the other, measuring strenth performance and the underlying neural mechanisms during real-life resistance training activities remains a challenging methodological task that limit our accurate understanding of the ultimate mechanisms underpining strength performance. From this perspective, the current work may serve as a basis for future research aiming to address the numerous interesting questions around the human exposure to limited oxygen availability and training adaptive responses. While basic research suggests that exposure to higher altitude does not influence a muscle's capacity to generate isometric force (Perrey and Rupp 2009), the more complex and specific strength manifestations found in athletic tasks (Feriche et al. 2014; Alhammoud et al. 2018) and resistance training practices (Ramos-Campo, Rubio-Arias, et al. 2017b) encourage further research.

## 4.1 Conclusions

*Preliminary research*

1) Three weeks of CMJ training including cluster set configurations are more efficient

at inducing velocity and power adaptations specific to the training load, although no changes in the FV-profile were nonetheless observed (Chapter 3.1).

2) Although clustering sets between repetitions clearly maintained mechanical power output during a training session, mixed responses were observed on the amplitude and spectral properties of the interference surface EMG signal. Limiting the number of repetitions per set and allowing complete resting periods seem enough to minimize muscle fatigue development (Chapter 3.2).

3) The maximal theoretical force ($F_0$), estimated from a FV profiling test during the CMJ exercise, is positively related with the knee extensors muscles maximal isometric strength, quadriceps thickness and VL pennation angle. On the contrary, the lack of association of $V_0$ with explosive isometric performance, voluntary neural activation and muscle morphological factors support previous findings reporting a weaker contribution of $V_0$ in the overall FV profile performance ($P_{max}$) compared to $F_0$, for this particular exercise (Chapter 3.3).

*Main conclusions*

4) Albeit similar MVIF and net mechanical performance during CMJ at moderate altitude, greater perceived exertion and performance decrements across repetitions may occur during heavy, but not light loading conditions. Notwithstanding, no meaninful differences between altitude levels or loading conditions were observed in the changes of the amplitude and spectral properties of the interference EMG signal across repetitions (Chapter 3.4).

5) In an active population, an 8-week power-oriented resistance training program of the lower body muscles result in similar dynamic (FV profile, CMJ performance and repeated CMJs) and maximal isometric strength adaptations. Likewise, comparable adaptations are observed in terms of muscle activation during isometric explosive unilateral knee-extension efforts and resting quadriceps muscle thickness, with the later showing region-specific adaptations (Chapter 3.5).

## 4.2 Conclusiones

*Estudios preliminares*

1) Tres semanas de entrenamiento de CMJ con el método cluster son más eficientes en la mejora del rendimiento explosivo específico a la carga de entrenamiento. Sin embargo, no se observaron cambios significativos en el perfil FV (Capítulo 3.1).

2) Aunque el método cluster maximizó el rendimiento de potencia durante una sesión de entrenamiento, los cambios en la amplitud y frecuencia de la señal de EMG no fueron claros. Un número reducido de repeticiones y descansos completos entre series parecen suficientes para minimizar el desarrollo de fatiga neuromuscular (Capítulo 3.2).

3) La fuerza máxima teórica estimada a partir del perfil FV obtenido en el ejercicio de CMJ está positivamente asociada con la fuerza isométrica máxima de los músculos extensores de la rodilla, su grosor muscular y ángulo de penneación. Por el contrario, la falta de asociación entre $V_0$ y la fuerza explosiva isométrica, la activación voluntaria o los factores morfológicos analizados están en línea con investigaciones precedentes que muestran una contribución limitada de dicho parámetro en el rendimiento general del perfil de FV (i.e. $P_{max}$ o $P_0$), para este ejercicio específico (CMJ vertical) (Capítulo 3.3).

*Conclusiones principales*

4) Aunque la MVIF y el rendimiento neto durante una sesión de entrenamiento de potencia no están afectados en altura moderada, la percepción del esfuerzo y la pérdida de rendimiento a lo largo de las repeticiones parecen estar aumentadas durante una sesión con cargas pesadas, pero no ligeras. No obstante, no se observó un efecto de la altitud en los cambios de la amplitud o frecuencia espectral de la señal de EMG (Capítulo 3.4).

5) En la muestra estudiada, 8 semanas de entrenamiento de fuerza orientado a la mejora de la potencia de piernas resultaron en cambios similares de fuerza dinámica (perfil FV, rendimiento en CMJ sobrecargado) y estática (fuerza isométrica máxima) fueron

observados en normoxia y altitud moderada. Además, las adaptaciones en el grosor muscular fueron también de magnitud similar entre los grupos (Capítulo 3.5).

# Chapter 5

# Future research

Suggestions for future research directions in the field of hypoxia and strength training could comprise:

- Exploring the influence of a "living high, train high" strategy on the muscle functional and physiological adaptations. This could be of particular interest for the numerous athletes often performing altitude training camps.
- Exploring the influence of resistance training under hypoxic conditions on running economy and endurance performance of elite athletes. The positive haematological consequences of living and training at altitude, along with the positive influence of strength training on running economy (Rønnestad and Mujika 2014) could provide a further positive effect on endurance performance.
- Investigating the influence of exposure to higher altitudes on motor unit behaviour using high-density EMG. Recent advances using this technique (Farina et al. 2016; Del Vecchio et al. 2017, Thompson et al. (2018)) may allow to experimentally adress the consequences of limited $O_2$ availability on muscle control.
- Comprehensively exaiming the adaptive responses of the active and passive elements of the MTU. Extending the resting ultrasound measurements completed in Experiment

3.5 to dynamic ultrafast recordings may help to gain a depper understanding of the particular changes that tendons and/or muscles undergo following resistance training under hypoxic conditions.

# Chapter 6

# Appendix: Reproducible examples and source code

The current section provides source code and reproducible examples of the signal proccessing procedures used in the methods of this doctoral thesis. According to the objective, the methodology is inherently related with the assessment of muscle strength performance. Different approaches have been employed to evaluate changes in the explosive and ballistic strength performance of the lower body muscles, following acute and chronic strength training interventions.

Dynamic and isometric approaches have been performed to evaluate maximal strength levels and the ability to produce high rates of force and power development. While the experimental approaches have mainly concerned functional outcomes (e.g. power output, force, RFD), other measurements have been carried out to get a better understanding of the underlying mechanisms. Surface electromyography (EMG) and ultrasound measurements have been used to evaluate muscle activation and muscle architecture, respectively.

Force, velocity and displacement recordings have been carried out through different devices that allow estimation of their respective integrated and derived variables. For example, GRF recordings have been used to calculate power output from the product of applied force and

COM velocity, integrated from COM acceleration. Isometric assessment of muscle strength has been possible thanks to the use of strain gauges and an unpadded rigid custom-made chair. It allowed isometric strength and RFD assessments in specific knee and hip angle positions.

Examples of the main data analysis steps are described below. Source code from custom-made functions and data examples are available at https://goo.gl/V9DQAT. Signal processing procedures have been performed in MATLAB (Version R2015a, The Mathworks, Natick, Massachusetts, USA). Statistics and figures have been computed using the R software (version 3.3.2, The R Foundation for Statistical Computing, 2016).

## 6.1 Countermovement jumps

The CMJ exercise, widely used to evaluate lower-limb strength performance, requires accelerating the body COM as much as possible, reaching the highest CM velocity possible in the shortest time. Measuring GRF using a force plate allows having a biomechanical analysis of CMJ performance. First, all data were imported from raw `.txt` files exported from the Kistler force plate software (Bioware V. 5.3, Kistler, Winterthur, Switzerland).

```
path_to_file = 'path\to\S1_participantX.txt';
GRFdata = importGRF(path_to_file);
F = double(GRFdata(:,2));
GRF = [GRFdata(:,2) F_filt];
```

Once the raw data from the `.txt` file has been imported (`GRFdata`), GRF is low pass filtered. `freq` is the low pass frequency and `Fs` the sampling frequency.

```
freq = 20;
Fs = 2000;
Wn = [freq]/(Fs*0.5);
[b,a] = butter(2,Wn,'low');
F_filt = filtfilt(b,a,F);
```

Different movement phases may be identified in a given CMJ repetition from the GRF data

(McMahon et al. 2018):

- **Stance phase:** the participant is required to stand still befor starting the repetition. This is a key step to get valid computation of velocity and power from GRF. Computation of COM displacement and velocity from GRF requires an accurate baseline to obtain accurate results (Linthorne 2001). By asking the participant to stand still during the weighing phase, we ensure that the COM velocity and displacement equal zero, which is an assumption when using forward dynamics to compute COM displacement and velocity through numerical integration (Street et al. 2001).

The GRF baseline has been computed using the `get_baseline.m` function. Baseline is computed as the mean of the GRF signal from the start of the signal to the onset of the repetition identified, which includes a period longer than 1s. An approximate onset (`idx`) is identified as the 3000th data point before the first index lower than 15N.

```
baseline = get_baseline(F_filt, 'no');

below_threshold = find(GRF < 15);
idx = below_threshold(1) - 3000;
BASELINE = mean(GRF(1:idx));

figure('units','normalized','outerposition', [0 0 1 1])
plot(GRF)
hold on
plot(GRF(1:idx),'--gs',...
    'MarkerSize',2,...
    'MarkerEdgeColor','r',...
    'MarkerFaceColor',[0.5,0.5,0.5])
hline = refline([0 BASELINE]);
hline.Color = 'r';
```

Once the `baseline` has been calculated during the weighing phase, segmentation of the signals is then performed to identify different phases of the CMJ movement. From the movement onset to the take-off instant, different movement phases have been defined:

- **Unweighing phase**: Period between the start of movement and the time instant at which GRF returns to the system weight.

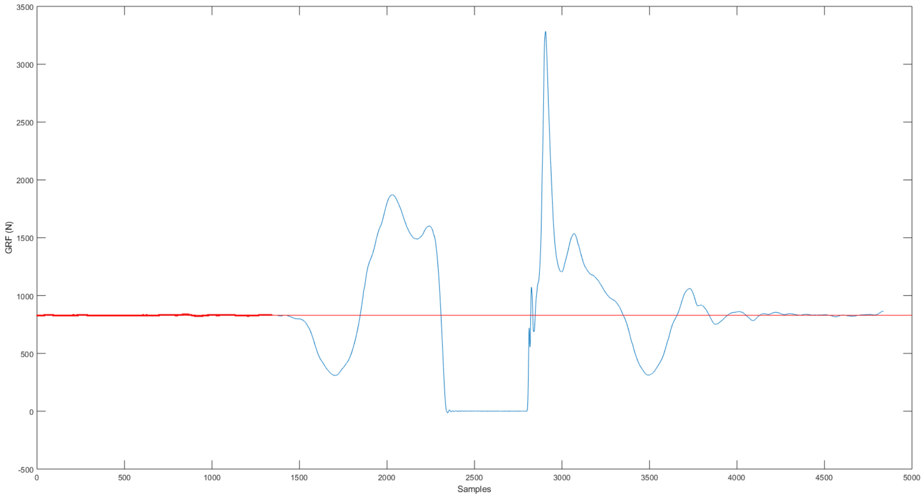

**Figure 6.1:** Snapshot of the figure output obtained from the `get_baseline.m` function in MATLAB. Detected baseline is highlighted in red. An average is taken as the system weight, which comprises both participant and external loads weights.

- **Braking phase**: Period comprised from the instant of peak negative COM velocity to the moment at which velocity is zero.
- **Concentric phase**: Period from the increase in COM velocity to the instant of take-off.

The custom made `find_indexes.m` function has been used to segmentate signals and calculate the variables of interest. The function takes as arguments the force plate signal `GRF`, the previosuly calculated `baseline`, the number of repetitions to be analysed in the set (`nreps`) and an optional argument `graph` to display the segmented repetition. Eventually, it returns the variable `INDEXES`, a matrix of dimensions `nreps` x 4 containing the data indexes at which the braking and concentric phases occur for later analysis.

```
g = 9.8;

% Find take off points
below_threshold = (GRF(:,2) < 25);
minAcceptableLength = 150;

% Find spans that are long enough.
isLongEnough = bwareafilt(below_threshold, [minAcceptableLength, inf]);
```

```matlab
% Count the number of spans that are long enough.
[labeledSpans, ~] = bwlabel(isLongEnough);

% repetition identification
takeoff_idx = zeros(nreps,1);
for ii = 1:nreps
    rep = find(labeledSpans == ii);
    takeoff_idx(ii,1) = rep(1);
end

% Find approximate onsets going back from take off instants
onset_idx = takeoff_idx - 1000;
onset_takeoff = [onset_idx takeoff_idx];

% Find now exact onsets
onsets = zeros(nreps,1);
for ii = 1:nreps
    ff = GRF(onset_takeoff(ii,1):onset_takeoff(ii,2)-1, 2);
    debajothreshold = (ff < baseline - 50);
    spanLocs = bwlabel(debajothreshold);
    spanLength = regionprops(spanLocs, 'area');
    spanLength = [ spanLength.Area];
    goodSpans = find(spanLength >= 200);
    allInSpans = find(ismember(spanLocs, goodSpans));
    indx_2 = allInSpans(1);
    onsets(ii,1) = (indx_2 + onset_takeoff(ii,1));
end

INDEXES = [onsets takeoff_idx];
```

Center of mass force, acceleration, displacement velocity and power values may be then analysed from the GRF signal, according to the impulse-momentum approach (Linthorne 2001). Computations have been performed using the function `analiza_GRF.m`, which takes as arguments:

- `data`: GRF signal vector.
- `baseline`: baseline computed from the `get_baseline.m` function.
- `indexes`: output from `find_indexes.m`.
- `height`: optional argument indicating if jump height (in cm) should be computed. This should be only used when indexes comprise the concentric phase.

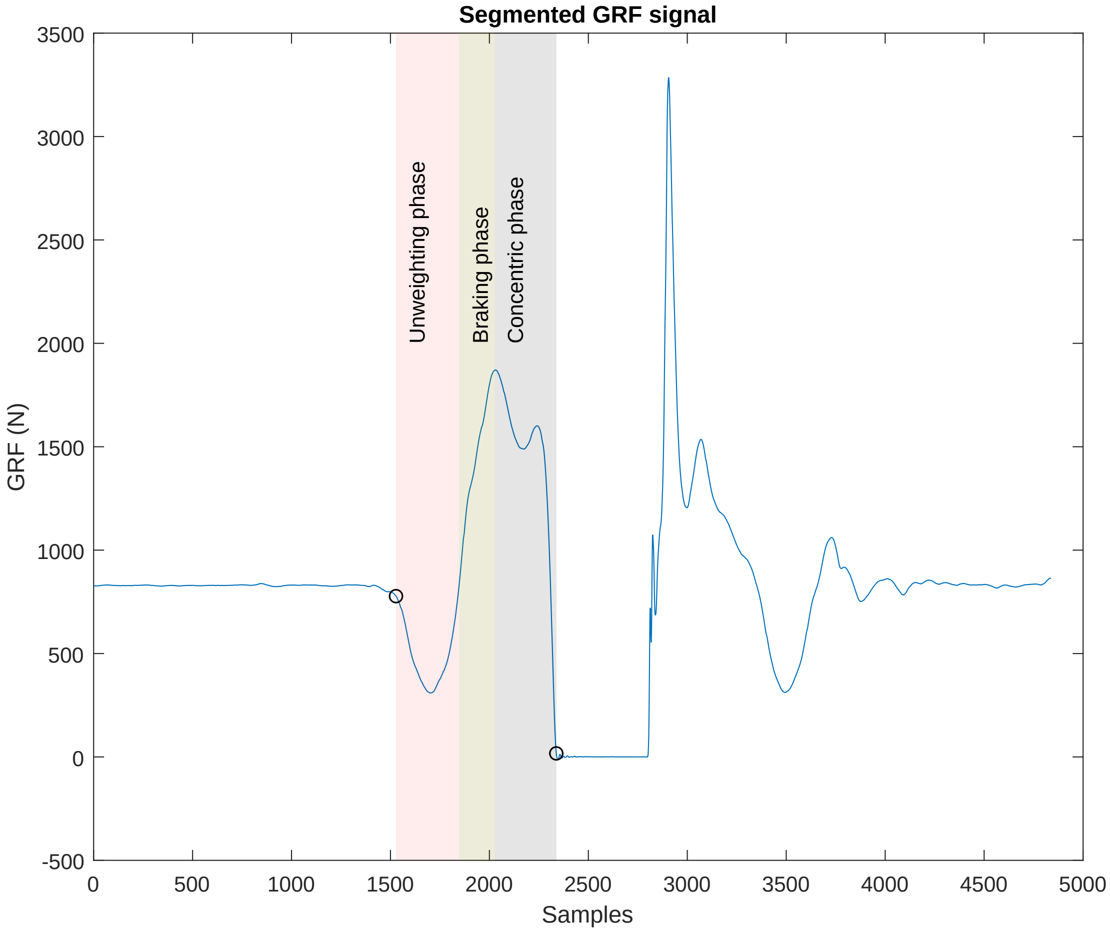

**Figure 6.2:** Snapshot of the Matlab figure showing a segmented GRF signal with the stance, braking and concentric phases indicated.

```
g = 9.8;

RESULT = zeros(9, size(indexes,1));
for ii = 1:size(indexes,1)
    time = data(indexes(ii,1):indexes(ii,2),1);
    force = data(indexes(ii,1):indexes(ii,2),2);
    f = force - baseline; %applied_force
    m = baseline/g;
    acc = f/m; % acceleration
    V =cumtrapz(time,acc);
    displacement = cumtrapz(time,V);
    P = force.*V;
    JUMP = [time force f acc V displacement P];

    F_mean = mean(JUMP(:,2));
    A_mean = mean(JUMP(:,4));
    V_mean = mean(JUMP(:,5));
    P_mean = mean(JUMP(:,7));

    F_peak = max(JUMP(:,2));
    A_peak = max(JUMP(:,4));
    V_peak = max(JUMP(:,5));
    P_peak = max(JUMP(:,7));
    D_peak = max(JUMP(:,6));

    RESULT(:,ii) = [F_mean A_mean V_mean P_mean ...
                    F_peak A_peak V_peak P_peak D_peak];
end
```

The output from `analiza_GRF.m` is a matrix containing peak and mean force, acceleration, velocity and power over the specific CMJ phase taken from `INDEXES`.

### 6.1.1 Force-velocity profile

An example of the calculation of the FV profile variables (`fvprofile.m`) is shown below. Sample data from six different loading conditions and two attempts at each load is provided in `fvprofile/data` as `.mat` files. They are first loaded and kept in two matrices containing all repetitions (`TIEMPOS` and `FUERZAS`):

```
for ii = 1:12
 load(['data/GRF_' num2str(ii) '.mat'])
end

TIEMPOS = padcat(GRF_01(:,1), GRF_02(:,1), GRF_03(:,1), GRF_04(:,1), ...
                 GRF_05(:,1), GRF_06(:,1), GRF_07(:,1), GRF_08(:,1), ...
                 GRF_09(:,1), GRF_10(:,1), GRF_11(:,1), GRF_12(:,1));

FUERZAS = padcat(GRF_01(:,2), GRF_02(:,2), GRF_03(:,2), GRF_04(:,2), ...
                 GRF_05(:,2), GRF_06(:,2), GRF_07(:,2), GRF_08(:,2), ...
                 GRF_09(:,2), GRF_10(:,2), GRF_11(:,2), GRF_12(:,2));
```

Thereafter, mean and peak force, acceleration, velocity and power values for each repetition are computed using the `analiza_GRF.m` function. A 12 by 9 matrix is contained in the variable `DATA`.

```
DATA = zeros(12,9);
for ii = 1:12
    GRF = [TIEMPOS(:,ii) FUERZAS(:,ii)];
    baseline = get_baseline(GRF(:,2), 'no');
    idxs = find_indexes(GRF, baseline, 1, 'no');
    DATA(ii,:) = analiza_GRF(GRF, baseline, idxs(3:4), 'no')';
end
```

Linear modelling of the force and velocity relationship is computed using the MATLAB custom built `polyfitn.m` function. The intercepts of the FV relationship with the force and velocity axes are used to calculate the maximal theoretical force (i.e. force value when velocity is 0; `Fmax`) and maximal theoretical velocity (i.e. velocity when force is 0; `Vmax`), respectively. The slope of the relationship ($\frac{F_0}{V_0}$) and maximal theoretical power (P$_0$; `Pmax`) (computed as $P_0 = \frac{F_0 \cdot V_0}{4}$) may be also computed.

```
[m,n] = size(DATA);
best_MEAN = zeros(m/2,n);
for ii=2:2:12
    [~, ind]= max([DATA(ii-1,3),DATA(ii,3)]);
    best_MEAN(ii/2,:)=DATA(ii-(ind==1),:);
end

F = best_MEAN(:,1);
V = best_MEAN(:,3);
```

```
F_V_relationship = polyfitn(V,F,1);
a = F_V_relationship.Coefficients(1,1);
Fmax = F_V_relationship.Coefficients(1,2);
Vmax = abs(Fmax/a);
Pmax = (Fmax*Vmax)/4;
```

### 6.1.2 Isometric strength assessments.

Maximal and explosive voluntary isometric strength assessments were performed on a custom-made isometric rigid dynamometer (Maffiuletti et al. 2016) with knee and hip angles of 110 and 130 degrees (180 = full extension), respectively. Pelvis and shoulders were firmly secured to the chair and a rigid strap was attached proximally to the ankle (2 cm above the lateral malleolus) in series with a calibrated low-noise strain gauge (Force Logic, Swallowfield, UK). The force signal from the strain gauge was amplified (× 370) and digitized at 1 kHz using a 16-bit analog to digital converter (DT 9804; Data Translation, Marlboro, Massachusetts, USA).

Signals from the strain gauge are first calibrated using the registered voltage values at known weights. Calibration was performed using the `calibration_force.m` function, which takes as argument the force signal vector in volts (`F_volts`) and returns the conversion in Newtons (`FORCE_N`). In the script, `x` and `y` values correspond to the known Newtons and Volts, respectively.

```
x = [0,1000,2000,3000,4000,5000];
y = [0.000, 1.996, 3.996, 5.998, 8.004, 10.023];
relationship = polyfitn(x,y,1);
coeficientes = relationship.Coefficients;
R2 = relationship.R2;
adjusted_R2 = relationship.AdjustedR2;
p1 = coeficientes(1,1);
p2 = coeficientes(1,2);
FORCE_N = (p2 + F_volts)/p1;
```

### 6.1.3 Maximal voluntary isometric contractions: isometric force and voluntary EMG activation.

A reproducible example of MVIF computation using MATLAB is provided. Precisely, the `data_example.mat` variable contains a *struct* object with raw force and EMG data during a knee extension maximal voluntary isometric contraction (`MVC_F` and `EMG_MVC`), which are both stored in a common matrix (`DATA_MVC`).

```
F_MVC = data_struct(ii).MVC_F;
F = calibration_force(F_MVC(:,2));
EMG_MVC = data_struct(ii).MVC_EMG;
```

Once calibrated, MVIF and maximal EMG activation values were calculated using the function `calcula_MVC.m`, which takes as argument `DATA_MVC`, and outputs the MVIF (`MVC_F`) and peak RMS for each muscle (`MVC_emg`).

Force signals recorded were filtered with a 4th order 150-Hz low pass Butterworth filter and were corrected for the influence of gravity during offline analysis.

```
Fs = 1926;
Fuerza = DATA_MVC(:,1);
F = filtra_signal(double(Fuerza), 150, Fs, 'low');
```

Thereafter, the number of registered contractions is identified and their indices are stored in the `attempt` variable for further proccessing:

```
above_threshold = F > abs(mean(F))*5;
minAcceptableLength = 400;
isLongEnough = bwareafilt(above_threshold, [minAcceptableLength, inf]);
[labeledSpans, numberofmaximos] = bwlabel(isLongEnough);

attempt = zeros(numberofmaximos,1);
for ii = 1:numberofmaximos
    rep = find(labeledSpans == ii);
    attempt(ii,1) = rep(ii);
end
```

The resting baseline is then automatically identified to allow gravity correction in all force measurements. Specifically, the force signal is splitted in 1-s chunks (`fuerza_reshaped`) and the ten one-second periods showing the least standard deviation are averaged to provide an average baseline (`BASELINE`).

```
segundos = round(length(F)/Fs)-1;
fuerza_reshaped = reshape(F(1:segundos*Fs)', [], segundos);

baseline_sds = zeros(1,size(fuerza_reshaped,2));
for ii = 1:size(fuerza_reshaped,2)
    baseline_sds(1,ii) = std(fuerza_reshaped(:,ii));
end

DATA_reshaped = [baseline_sds' mean(fuerza_reshaped,1)'];
S = sortrows(DATA_reshaped);
BASELINE = mean(S(1:10,2),1);
```

Once the baseline is identified, the maximal voluntay isometric force (gravity-corrected) can be calculated. First, all MVIC attempts are analysed and the highest peak force (`MVC_F`) and its index (`idx_mvc`) are kept for further analysis. Keeping the index where `MVC_F` occurs allows to later analyze EMG data in the same contraction, when the criteria of the contraction of the highest peak force applies.

```
MVFs = zeros(2,length(attempt));
for ii = 1:length(attempt)
    [mvf,idx] = max(F(attempt(ii):attempt(ii)+Fs*5));
    MVFs(1,ii) = mvf-BASELINE;
    MVFs(2,ii) = idx + attempt(ii);
end

SS = sortrows(MVFs');
MVC_F = SS(end,1);
idx_mvc = SS(end,2);
```

Next, EMG signals are band-pass filtered and EMG RMS (`MVC_emg`) may be computed as shown below. EMG RMS is averaged using a 250 ms (each side of peak) window:

```
EMG = DATA_MVC(:,2:4);
EMG_RMS = rms_emg(filtra_signal(double(EMG),[6,450],Fs,'bandpass','no'),
                  round(Fs*0.05));
MVC_emg = mean(EMG_RMS(idx_mvc-(Fs*0.25):idx_mvc+(Fs*0.25),:),1);
```

### 6.1.4 Explosive voluntary isometric force

The assessment of explosive force production capacity, often described as rate of force development (RFD), has been shown to be most reliable under single joint isometric conditions (Maffiuletti et al. 2016). These reduce the amount of potential coundfounding factors affecting RFD such as changes in the muscle-tendon unit. Moreover, different parameters from the force-time curve can be obtained to inform about the fast force production:

- Force at different times from the onset
- Rate of force or torque development

Considering the short time periods over which explosive performance is examined, there are material and methodological sources of variation that should be considered:

- Onset detection: pre tension and co-contraction issues.
- Isometric apparatus: padded, joint movement.

#### 6.1.4.1 Onset identification

Force signals recorded during the explosive voluntary contractions were first analysed to determine contraction onset and to discard any attempt with pre-tension or countermovement before contraction onset. Force onsets were automatically identified and visually confirmed, as the last zero-crossing point on the first derivative of the filtered signal force. The function `encuentra_onsets.m` takes as argument `DATA_EXPL`, which is a matrix containing both force and EMG data recorded during an explosive isometric knee extension assessment. Other arguments (`graph_force` and `graph_emg`) are used to indicate wether we want to show pltos with the identified onsets.

Following signal filtering, the total number of repetitions and their index location are found as follows and kept in the `maximos` variable:

```
ff = diff(fuerza_filt);
F = fuerza_filt;
above_threshold = F > abs(max(F))*0.5;
minAcceptableLength = 300;
isLongEnough = bwareafilt(above_threshold, [minAcceptableLength, inf]);
[labeledSpans, numberofmaximos] = bwlabel(isLongEnough);

maximos = zeros(numberofmaximos,1);
for ii = 1:numberofmaximos
    rep = find(labeledSpans == ii);
    maximos(ii,1) = rep(ii);
end
```

Thereafter, for each identified contraction, whose index is in `maximos`, the specific part of the signal 1000 samples of the signal before (i.e. baseline) and after the real onset contraction is identified and saved in the `cachos` matrix of dimensions 1000 x N (where N equals `length(maximos)`).

```
cachos_iniciales = zeros(1000, length(maximos));
for kk = 1:length(maximos)
    cachos_iniciales(:,kk) = ff(maximos(kk)-999:maximos(kk));
end
```

The precise onset locations for each contraction are computed. On this purpose, and to ensure that any spikes in the signal do not affect the onset location, the baseline prior to the onset.

To avoid delayed onset detection due to (unlikely) spikes in the filtered force signal, the range of the baseline values is used to ensure that detected onsets are not greater than the greatest value observed during the baseline period. Precisely, onset index is as the last zero-crossing point on the first derivative of the filtered signal force. For each contraction, the matrix `ONSETS_F` contains each corresponding onset.

```
onsets = zeros(1, size(cachos_iniciales,2));
for kk = 1:size(cachos_iniciales,2)
   idx = find(cachos_iniciales(:,kk) < 0);
   onsets(1,kk) = idx(end) + (maximos(kk)-1000);
end
```

```
ONSETS_F = zeros(1, length(onsets));
for ii = 1:size(onsets,2)
    repeticion = F(onsets(1,ii)-999:onsets(1,ii)+200,1);
    baseline = F(onsets(ii)-(Fs*0.2):onsets(ii)-(Fs*0.05));
    max_baseline = max(baseline);
    mean_baseline = mean(baseline);

    ff = diff(repeticion);

    idx = find(ff < 0);

    Fvalues = repeticion(idx);
    ONSETS_max_baseline(1,ii) = idx(find(Fvalues <= max_baseline, 1, 'last')) + ...
    (onsets(ii)-1000);
end

ONSETS_F = ONSETS_max_baseline;
```

#### 6.1.4.2 Explosive repetition selection

From all explosive contractions performed, the three attempts with the highest force at 100 ms were further analysed and eventually averaged across. Accordingly, different steps are taken to automate the contraction selection proccess acording to three different criteria:

1. Noisy baseline
2. Maximal attained force.

To discard any contraction with pre-tension or countermovement, 100 ms baseline force signals prior to contraction onset were fitted with a least-squares linear regression, and absolute slope values greater than 1.5 $N \cdot m \cdot s^{-1}$ were set as a criterion for contraction omission due to potential effects of co-contraction or countermovement on explosive performance (de Ruiter et al. 2007). Explosive contractions reaching peak force < 75% MVT were also discarded.

All these steps are wrapped up in the `clean_contractions` function, which takes as arguments the explosive force data (`DATA_EXPL`), the onsets found for each contraction using the `encuentra_onsets.m`.

- Condition 1: Discard contractions with pre-tension or co-contraction 100 ms before onset.

```
for ii = 1:length(ONSETS_F)
    Fs = 1926;
    repeticion = DATA_EXPL_filtered(ONSETS_F(1,ii)-2000:ONSETS_F(1,ii)+3999,1);
    onset = 2001;
    pre_base = repeticion(onset - (Fs*0.15):onset);
    x = (1:length(pre_base))';
    y = pre_base;
    [fitresult, ~] = createFit(x, y);
    coeffvals = coeffvalues(fitresult);
    p1 = abs(coeffvals(1,1)*Fs)*Lever_arm;
    ONSETS_F(2,ii) = p1;
end

idx_keep = ONSETS_F(2,:) < 2.5;
id = idx_keep == 1;
contractions_to_keep = ONSETS_F(:,id);

if sum(idx_keep) == 0
    ranking = sortrows(ONSETS_F',2);
    contractions_to_keep(:,1:3) = ranking(1:3,:)';

elseif sum(idx_keep) == 1
    ranking = sortrows(ONSETS_F',2);
    contractions_to_keep(:,2:3) = ranking(2:3,:)';

elseif sum(idx_keep) == 2
    ranking = sortrows(ONSETS_F',2);
    contractions_to_keep(:,3) = ranking(3,:)';
end

idx_delete = setdiff(ONSETS_F(1,:),(contractions_to_keep(1,:)));
for ii = 1:length(idx_delete)
    DATA_EXPL(idx_delete(1,ii)-2000:idx_delete(1,ii)+4999,:) = 0;
end

SELECTED_CONTRACTIONS = DATA_EXPL;
```

- Condition 2: Rank all contractions left and leave only those achieving a peak force greater than 75% MVIC.

```
if size(contractions_to_keep,2) == 3
    SELECTED_CONTRACTIONS = SELECTED_CONTRACTIONS;

elseif size(contractions_to_keep,2) > 3
    for ii = 1:length(contractions_to_keep)
        repeticion = SELECTED_CONTRACTIONS(contractions_to_keep(1,ii)-2000: ...
                                   contractions_to_keep(1,ii)+3999,1);
        onset = 2001;
        pre_base = repeticion(onset - Fs*0.1:onset);
        maximo = max(repeticion) - mean(pre_base);

        contractions_to_keep(3,ii) = maximo;
        contractions_to_keep(4,ii) = (maximo*100)/MVC_F;
    end

    idx_max = contractions_to_keep(4,:) > 75;

    if sum(idx_max) == 0
        ranking = flip(sortrows(contractions_to_keep',4));
        contractions_to_keep(:,1:3) = ranking(1:3,:)';

    elseif sum(idx_max) == 1
        ranking = flip(sortrows(contractions_to_keep',4));
        contractions_to_keep(:,2:3) = ranking(2:3,:)';

    elseif sum(idx_max) == 2
        ranking = flip(sortrows(contractions_to_keep',4));
        contractions_to_keep(:,3) = ranking(3,:)';

    elseif sum(idx_max) >= 3
        id = find(idx_max == 1);
        contractions_to_keep = contractions_to_keep(:,id);
    end

    idx_delete = setdiff(ONSETS_F(1,:),(contractions_to_keep(1,:)));
    for ii = 1:length(idx_delete)
        SELECTED_CONTRACTIONS(idx_delete(1,ii)-2000: ...
                              idx_delete(1,ii)+4999,:) = 0;
    end
end
```

- Condition 3: From all contractions left, take the three with the highest force at 100 ms after onset, and average them accross.

```
if size(contractions_to_keep,2) <= 3
    SELECTED_CONTRACTIONS = SELECTED_CONTRACTIONS;
else
    for ii = 1:size(contractions_to_keep,2)
        F = SELECTED_CONTRACTIONS(:,1);
        repeticion = F(contractions_to_keep(1,ii)-2000: ...
                       contractions_to_keep(1,ii)+(Fs*0.1));
        onset = 2001;
        baseline = mean(repeticion(onset - (Fs*0.5):onset),1);
        contractions_to_keep(5,ii) = repeticion(end) - baseline;
    end

    ranking = flip(sortrows(contractions_to_keep',5));
    contractions_to_keep = ranking(1:3,:);

    idx_delete = setdiff(ONSETS_F(1,:),(contractions_to_keep(:,1)'));
    for ii = 1:length(idx_delete)
        SELECTED_CONTRACTIONS(idx_delete(1,ii)-2000: ...
                              idx_delete(1,ii)+4999,:) = 0;
    end
```

### 6.1.5 Surface electromyography

#### 6.1.5.1 Cross-correlation synchronization

Example data is provided in the `data_example_sync.mat` file, which contains a `struct` object with raw GRF and EMG data collected during a set of continuous CMJ repetitions. Signals have been registered from different devices and triaxial accelerometry built-in within the EMG sensors (Trigno Sensor; Delsys Boston, Massachusetts, USA) was used to synchronize EMG and GRF signals during offline signal processing. An EMG sensor was firmly attached to the Smith Machine barbell and used to acquire accelerometry data synchronized with EMG.

```
for ii = 1

    S = DATABASE(ii).RAW.SET;

    for kk = 1:size(S,2)
```

```
        EMG = [S(kk).EMG];
        ACC_all = [S(kk).ACC_all];
        FzN = [S(kk).FzN];
        baseline = DATABASE(ii).RAW.baseline.baseline;

        [ SYNC ] = sincroniza_EMG(EMG, ACC_all, FzN, baseline);
        [ DATOS ] = segmenta_calcula(SYNC, baseline);

        CALCULOS(kk).DATOS = DATOS;

    end

    % Horizontal concatenation to have all repetitions (36) results in a same array
    DATABASE(ii).RESULTS = cell2mat(arrayfun(@(x) horzcat(x.DATOS), ...
                                             CALCULOS,'UniformOutput', false));

    % Calculate the mean every 6 repetitions
    DATABASE(ii).AVERAGED = squeeze( ...
                            mean(reshape(DATABASE(ii).RESULTS.',6,[],17),2));
end
```

The function `sincroniza_EMG` performs a series of stepts to aling `EMG` and `GRF` signals. GRF, EMG and acceleration signals are first “cleaned” (removed initial zeros from the export proccess and resample `FzN`) using the functions `clean_EMG`, `clean_FzN` and `clean_ACC`, respectively. Acceleration data from the EMG sensor isthen combined into a one-dimensional signal representing the acceleration along the Z axis by applying an optimal rotation matrix obtained by Singular Value Decomposition, using the `optimalrotation.m` function, whose `( X, Y, Z, ini, fin)` as arguments and `Bout` as output:

```
N = fin-ini+1;
A = [X(ini:fin) Y(ini:fin) Z(ini:fin)];
Normal = sqrt(X.^2+Y.^2+Z.^2);
B = [zeros(N,1) zeros(N,1) Normal(ini:fin)];

H = A'*B;
[U,S,V] = svd(H);
R = V*U';

if det(R) < 0
   fprintf('Detectada una reflexión\n');
   V(:,3) = -V(:,3);
   R = V*U';
end
```

```
A=[X Y Z];
Bout = R*A';
```

Acceleration signals from the force plate and EMG-sensor devices are then aligned using the MATLAB builtin funtion `alignsignals.m`. The number of samples by which the two input signals, `X` and `Y` are offset is calculated and used to fill with zeros, providing the matrix `SYNC` which contains both aligned signals:

```
m = baseline/9.8; % mass (kg)
f = FzN - baseline; %applied_force
aceleration_2 = f/m; % aceleración plataforma
aceleration_1 = ACC(:,1);

X = aceleration_1; % aceleracion a partir del aparato de EMG
Y = aceleration_2; % aceleración a partir de la FzN

EMG_DATA = [EMG ACC];

[Xa,Ya,D] = alignsignals(X,Y,[],'truncate');

if D > 0
    EMG_DATA = padarray(EMG_DATA, [abs(D)],'pre');
else
    FzN = padarray(FzN, abs(D), 'pre');
    aceleration_2 = padarray(aceleration_2, abs(D), 'pre');
end

shortest = min(length(FzN), length(EMG_DATA));
EMG_DATA = EMG_DATA(1:shortest,:);
FzN = FzN(1:shortest);

[ SYNC ] = [FzN EMG_DATA];
```

Onsets and take-offs for each repetition are automatically identified:

```
m = baseline/g;
f = F - baseline;
acc = f/m;

onset_idx = takeoff_idx - 2500;
onset_takeoff = [onset_idx takeoff_idx];

onsets = zeros (6,1);
```

```
for ii = 1:6
    ff = F(onset_takeoff(ii,1):onset_takeoff(ii,2)-1);
    debajothreshold = (ff < baseline - 50);
    spanLocs = bwlabel(debajothreshold);
    spanLength = regionprops(spanLocs, 'area');
    spanLength = [ spanLength.Area];
    goodSpans = find(spanLength >= 200);
    allInSpans = find(ismember(spanLocs, goodSpans));
    indx_2 = allInSpans(1);
    onsets(ii,1) = (indx_2 + onset_takeoff(ii,1));
end

INDEXES = [onsets takeoff_idx];
```

Onsets and take-off indexes may be visualized using the following code:

```
indexes = [onsets; takeoff_idx];
figure
hold
for ii = 1:size(indexes,1)
    plot(F);
    plot(indexes(ii),F(indexes(ii)),'ko');
end
```

Concentric phases are identified, and mechanical variables of interest may be calculated as shown above using the `analiza_GRF.m` functions above shown:

```
v_index = zeros(6,1);
for ii = 1:6
    jump = (SYNC(INDEXES(ii,1):INDEXES(ii,2),:));
    time = jump(:,1);
    force = jump(:,2);
    f = force-baseline; %applied_force
    acc = f/m;
    V = cumtrapz(time,acc);
    idx = find(V > 0);
    v_index(ii,1) = idx(1) + INDEXES(ii,1);
end

INDEXES = [onsets takeoff_idx];
CONCENTRICO_idx = [v_index takeoff_idx]
```

Segmented EMG and GRF signals may be plotted, as shown in Figure 6.3:

```
S = SYNC;
EMG = S(:,3:5)/(max(S(:,3))*10);
FzN = S(:,2)*0.0001;
S = [FzN EMG];
figure
plot(S);
title('Señales de fuerza y electromiografía (sincronizadas y segmentadas)')
xlabel('Data points')
ylabel('Fuerza (N) y EMG (V)')
hold
ax = gca;
ax_limy = zeros(6,1);
ax_limx = zeros(6,1);
for ii = 1:6
    ax_limy(ii,1) = ax.YLim(1);
    ax_limx(ii,1) = ax.YLim(2)-ax.YLim(1);
    indexes_rectangle = [CONCENTRICO_idx(ii,1) ax_limy(ii) ...
                         CONCENTRICO_idx(ii,2)-CONCENTRICO_idx(ii,1) ax_limx(ii)];
    rectangle('Position',indexes_rectangle, 'LineWidth',1, 'EdgeColor','r');
end
```

EMG amplitude (RMS) and spectral parameters ($F_{\mathrm{med}}$, $FI_{\mathrm{nsmk}}$) may be obtained using the `analiza_EMG.m` function on the filtered EMG data:

```
function RESULT = analiza_EMG(EMG_DATA, indexes, Fs, Fmin, Fmax)

for ii = 1:size(indexes,1)
    EMG = EMG_DATA(indexes(ii,1):indexes(ii,2),:);
    RMS(:,ii) = rms(EMG);
    Fmed(:,ii) = medfreq(EMG, Fs);
    for j=1:size(EMG,2)
        FI5(j,ii) = FIindex(EMG(:,j),5, Fmin, Fmax, Fs);
    end
end

RESULT = [RMS; Fmed; FI5];

end
```

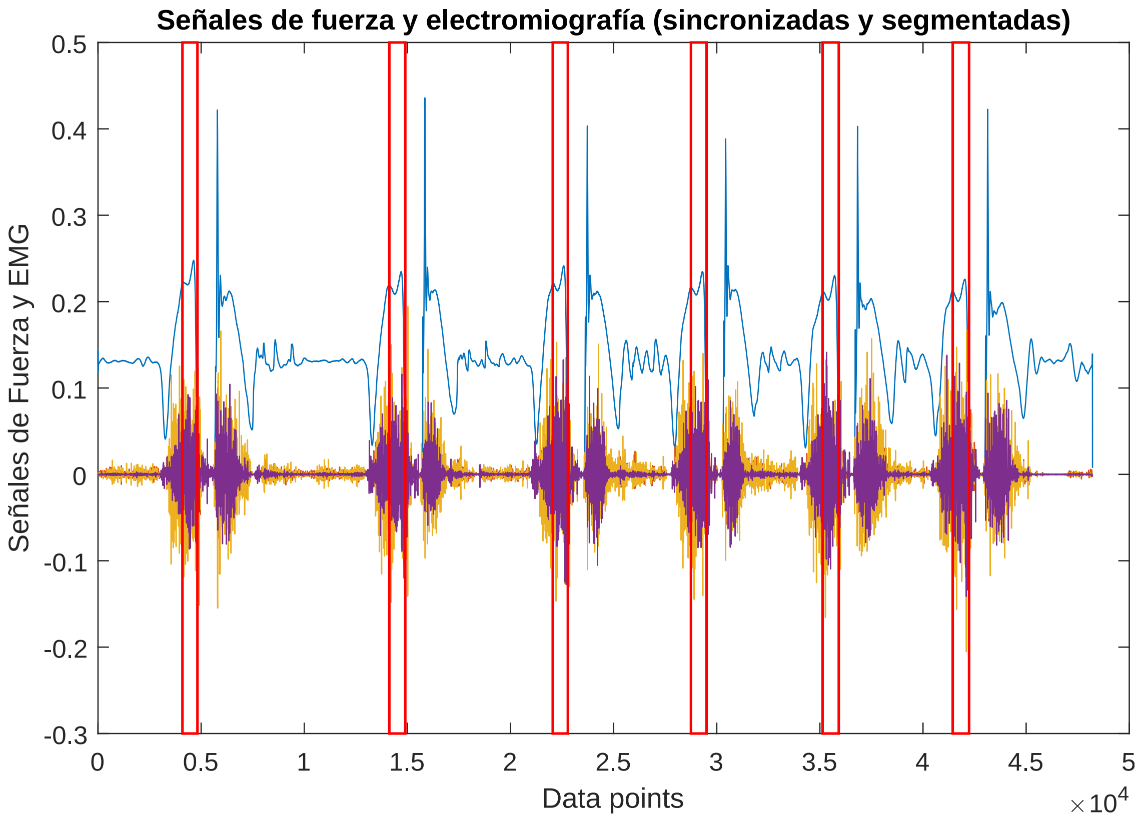

**Figure 6.3:** Snapshot of the figure output obtained from the `segmenta_calcula.m` function in MATLAB. Red rectangles delimit concentric phases for each CMJ repetition. GRF (blue) and EMG (red, yellow, purple) signals scales have been normalized for visualization purposes.

## 6.2 Isometric contractions

During explosive contractions, EMG onset was manually identified as the first muscle to be activated. Specifically, raw EMG signals were graphically displayed with systematic x and y-axis (i.e., 300ms and ± 0.05mV, respectively) before manually selecting the last point at which the signal deflected away from baseline (Balshaw et al., 2016). Thereafter, RMS EMG was averaged over three periods from the EMG onset: 0-50ms, 50-100ms, and 100-150ms (EMG0-50, EMG50-100, EMG100-150, respectively), normalized to EMGMVF and averaged across muscles.

The function `selecciona_onsets.m` takes as arguments the explosive data containing EMG signals (`ALL_DATA`) and a matrix containing approximate EMG onsets calculated from the `encuentra_onsets.m` function (`EARLIEST_EMG_ONSETS`). It outputs the indexes of the onsets manually selected (`MANUAL_ONSETS`).

```
EMG = ALL_DATA(:,5:7);
Fs = 1926;

MANUAL_ONSETS = zeros(1, length(EARLIEST_EMG_ONSETS));
for ii = 1:length(EARLIEST_EMG_ONSETS)

    repeticion = EMG(EARLIEST_EMG_ONSETS(1,ii)-(Fs*0.25): ...
                     EARLIEST_EMG_ONSETS(1,ii)+(Fs*0.25),:);
    figure('units','normalized','outerposition',[0 0 1 1])
    plot(repeticion)
    ylim([-0.0005 0.0005])
    hold
    xx = ginput(1);
    ini = round(xx(1));
    hold off
    close
    idx_manual = ini;
    MANUAL_ONSETS(1,ii) = round((EARLIEST_EMG_ONSETS(1,ii)-(Fs*0.25)) + ...
                                idx_manual);
```

# Acknowledgements

Dado el tiempo y esfuerzo que ha llevado llegar hasta aquí, es inevitable mirar atrás y sentirse agradecido con todas aquellas personas que de una forma u otra han formado parte del camino.

En primer lugar, me gustaría agradecer a mi profesora Belén Feriche su constante ayuda y trabajo a lo largo de estos años. Gracias por darme la primera oportunidad de conocer lo que hoy considero mi pasión y facilitarme el camino en todo momento.

Quiero dar las gracias a todos los compañeros sin los cuales este trabajo no hubiera sido posible. Gracias Paulino, Amador, Alejandro, Filipa y Juan por vuestra ayuda y los momentos compartidos. De corazón, os deseo lo mejor. A la dirección y los compañeros del CAR de Sierra Nevada. Javi, Blanca y Carmen, gracias por vuestro apoyo y por hacerme sentir como en casa siempre. ¡Mil gracias!

A los profesores del Departamento de Teoría de la Señal de la Universidad de Granada. Antonio M. Peinado, Ángel Gómez y José Luis Pérez, estaré siempre agradecido por vuestro amable recibimiento y ayuda con el procesamiento de señales. Gracias a Borja, Guille, Javi, Fer y todos los compañeros "de fatigas" de la Facultad. Gracias por vuestro apoyo y todos los momentos compartidos. ¡Os deseo lo mejor!

Agradecer también a todas aquellas personas que han participado como sujetos experimentales. Sin vosotros, este trabajo no sería posible. A todo el equipo de Valencia Club de Judo. No solo sois grandes deportistas, sino también grandes personas.

I would like to express my most sincere gratitude to all colleagues from INSEP. Gaël, I will be always grateful for your trust and guidance. Thank you Lilian, it was a real pleasure working with you! Simon, Enzo, Mathilde, Robin, Anis and all those INSEPiens that I have been lucky to meet along the way, thank you for making me feel like at home from the first day. Merci beaucoup!

A todos los familiares y amigos que formáis parte de mi vida y le dais sentido. Papá, mamá, no hay palabras para expresar y agradecer vuestro cariño y amor, sin los cuales, nada sería posible. A los que ya no están, a mis héroes, a mis abuelos. Gracias a la vida por permitirnos disfrutar y aprender con ellos. Abuela, no hemos podido celebrar el fin de esta etapa juntos, pero te llevo siempre en el corazón.

A ti, Marine. No hay palabras para agradecerte todo lo que haces por mí. Tampoco las hay para expresar todo lo que siento por ti. Gracias por tu constante apoyo y amor. Gracias por creer en mí, en nosotros. Porque tú y yo sabemos que no hay distancia, idioma o contratiempo que nos separe. Porque tú eres tú, y yo soy yo, y eso es maravilloso.

# References

Aagaard, P. 2003. "Training-Induced Changes in Neural Function." *Exercise and Sport Sciences Reviews* 31 (2): 61–67.

Aagaard, P., and Alf Thorstensson. 2003. "Neuromuscular Aspects of Exercise by Strength Training." In *Textbook of Sports Medicine*, edited by Michael Kjr, Michael Krogsgaard, Peter Magnusson, Lars Engebretsen, Harald Roos, Timo Takala, and Savio L-Y Woo, 70–106. Oxford, UK: Blackwell Science Ltd. doi:10.1002/9780470757277.ch4.

Aagaard, P., J. L. Andersen, P. Dyhre-Poulsen, A. M. Leffers, A. Wagner, S. P. Magnusson, J. Halkjaer-Kristensen, and E. B. Simonsen. 2001. "A Mechanism for Increased Contractile Strength of Human Pennate Muscle in Response to Strength Training: Changes in Muscle Architecture." *The Journal of Physiology* 534 (Pt. 2): 613–23.

Aagaard, P., Erik B. Simonsen, Jesper L. Andersen, Peter Magnusson, and Poul Dyhre-Poulsen. 2002a. "Neural Adaptation to Resistance Training: Changes in Evoked V-Wave and H-Reflex Responses." *Journal of Applied Physiology* 92 (6): 2309–18. doi:10.1152/japplphysiol.01185.2001.

———. 2002b. "Increased Rate of Force Development and Neural Drive of Human Skeletal Muscle Following Resistance Training." *Journal of Applied Physiology* 93 (4): 1318–26. doi:10.1152/japplphysiol.00283.2002.

Ahtiainen, Juha P., and Keijo Häkkinen. 2009. "Strength Athletes Are Capable to Produce Greater Muscle Activation and Neural Fatigue During High-Intensity Resistance Exercise

Than Nonathletes." *The Journal of Strength & Conditioning Research* 23 (4): 1129–34.

Alhammoud, Marine, Baptiste Morel, Olivier Girard, Sebastien Racinais, Violaine Sevrez, Alexandre Germain, Thomas Chamu, and Christophe Hautier. 2018. "Hypoxia and Fatigue Impair Rapid Torque Development of Knee Extensors in Elite Alpine Skiers." *Frontiers in Physiology* 9 (July). doi:10.3389/fphys.2018.00962.

Amann, Markus, and Bengt Kayser. 2009. "Nervous System Function During Exercise in Hypoxia." *High Altitude Medicine & Biology* 10 (2): 149–64. doi:10.1089/ham.2008.1105.

Andersen, Lars L., and P. Aagaard. 2006. "Influence of Maximal Muscle Strength and Intrinsic Muscle Contractile Properties on Contractile Rate of Force Development." *European Journal of Applied Physiology* 96 (1): 46–52. doi:10.1007/s00421-005-0070-z.

Arbogast, S., T. Vassilakopoulos, J. L. Darques, J. B. Duvauchelle, and Y. Jammes. 2000. "Influence of Oxygen Supply on Activation of Group IV Muscle Afferents After Low-Frequency Muscle Stimulation." *Muscle & Nerve* 23 (8): 1187–93.

Arnold, Todd W. 2010. "Uninformative Parameters and Model Selection Using Akaike's Information Criterion." *The Journal of Wildlife Management* 74 (6): 1175–8. doi:10.1111/j.1937-2817.2010.tb01236.x.

Arsac, Laurent M. 2002. "Effects of Altitude on the Energetics of Human Best Performances in 100 M Running: A Theoretical Analysis." *European Journal of Applied Physiology* 87 (1): 78–84. doi:10.1007/s00421-002-0587-3.

Badier, M., C. Guillot, F. Lagier-Tessonnier, and Y. Jammes. 1994. "EMG Changes in Respiratory and Skeletal Muscles During Isometric Contraction Under Normoxic, Hypoxemic, or Ischemic Conditions." *Muscle & Nerve* 17 (5): 500–508. doi:10.1002/mus.880170506.

Bakeman, Roger. 2005. "Recommended Effect Size Statistics for Repeated Measures Designs." *Behavior Research Methods* 37 (3): 379–84.

Baker, D., G. Wilson, and B. Carlyon. 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): 350–55.

Baker, Daniel G., and Robert U. Newton. 2008. “Comparison of Lower Body Strength, Power, Acceleration, Speed, Agility, and Sprint Momentum to Describe and Compare Playing Rank Among Professional Rugby League Players.” *Journal of Strength and Conditioning Research* 22 (1): 153–58. doi:10.1519/JSC.0b013e31815f9519.

Balshaw, Thomas G., Garry J. Massey, Thomas M. Maden-Wilkinson, Antonio J. Morales-Artacho, Alexandra McKeown, Clare L. Appleby, and J. P. Folland. 2017. “Changes in Agonist Neural Drive, Hypertrophy and Pre-Training Strength All Contribute to the Individual Strength Gains After Resistance Training.” *European Journal of Applied Physiology* 117 (4): 631–40. doi:10.1007/s00421-017-3560-x.

Balshaw, Thomas G., Garry J. Massey, Thomas M. Maden-Wilkinson, N. A. Tillin, and J. P. Folland. 2016. “Training-Specific Functional, Neural, and Hypertrophic Adaptations to Explosive- Vs. Sustained-Contraction Strength Training.” *Journal of Applied Physiology* 120 (11): 1364–73. doi:10.1152/japplphysiol.00091.2016.

Bamman, M. M., B. R. Newcomer, D. E. Larson-Meyer, R. L. Weinsier, and G. R. Hunter. 2000. “Evaluation of the Strength-Size Relationship in Vivo Using Various Muscle Size Indices.” *Medicine and Science in Sports and Exercise* 32 (7): 1307–13.

Batterham, Alan M., and William G. Hopkins. 2006. “Making Meaningful Inferences About Magnitudes.” *International Journal of Sports Physiology and Performance* 1 (1): 50–57.

Bazuelo-Ruiz, Bruno, P. Padial, Amador García-Ramos, Antonio J. Morales-Artacho, María T. Miranda, and Belén Feriche. 2015. “Predicting Maximal Dynamic Strength from the Load-Velocity Relationship in Squat Exercise.” *Journal of Strength and Conditioning Research* 29 (7): 1999–2005. doi:10.1519/JSC.0000000000000821.

Bärtsch, P, and B Saltin. 2008. “General Introduction to Altitude Adaptation and Mountain Sickness.” *Scandinavian Journal of Medicine & Science in Sports* 18 Suppl 1 (August): 1–10.

doi:10.1111/j.1600-0838.2008.00827.x.

Behm, D. G., and D. G. Sale. 1993. “Intended Rather Than Actual Movement Velocity Determines Velocity-Specific Training Response.” *Journal of Applied Physiology* 74 (1): 359–68.

Bell, D. G., and I. Jacobs. 1986. “Electro-Mechanical Response Times and Rate of Force Development in Males and Females.” *Medicine and Science in Sports and Exercise* 18 (1): 31–36.

Bird, Stephen P, Kyle M Tarpenning, and Frank E Marino. 2005. “Designing Resistance Training Programmes to Enhance Muscular Fitness: A Review of the Acute Programme Variables.” *Sports Medicine* 35 (10): 841–51. doi:10.2165/00007256-200535100-00002.

Blazevich, A. 2018. “Adaptations in the Passive Mechanical Properties of Skeletal Muscle to Altered Patterns of Use.” *J Appl Physiol*, 32.

Blazevich, Anthony J. 2006. “Effects of Physical Training and Detraining, Immobilisation, Growth and Aging on Human Fascicle Geometry.” *Sports Medicine* 36 (12): 1003–17. doi:10.2165/00007256-200636120-00002.

Blazevich, Anthony J., and N. C Craig Sharp. 2005. “Understanding Muscle Architectural Adaptation: Macro- and Micro-Level Research.” *Cells Tissues Organs* 181 (1): 1–10. doi:10.1159/000089964.

Blazevich, Anthony J., David R. Coleman, Sara Horne, and Dale Cannavan. 2009. “Anatomical Predictors of Maximum Isometric and Concentric Knee Extensor Moment.” *European Journal of Applied Physiology* 105 (6): 869–78. doi:10.1007/s00421-008-0972-7.

Blazevich, Anthony J., Nicholas D. Gill, and Shi Zhou. 2006. “Intra- and Intermuscular Variation in Human Quadriceps Femoris Architecture Assessed in Vivo.” *Journal of Anatomy* 209 (3): 289–310. doi:10.1111/j.1469-7580.2006.00619.x.

Blazevich, Anthony J., Nicholas D. Gill, Roger Bronks, and Robert U. Newton. 2003.

“Training-Specific Muscle Architecture Adaptation After 5-Wk Training in Athletes.” *Medicine and Science in Sports and Exercise* 35 (12): 2013–22. doi:10.1249/01.MSS.0000099092.83611.20.

Blazevich, Anthony J., Nicholas D. Gill, Nathan Deans, and Shi Zhou. 2007. “Lack of Human Muscle Architectural Adaptation After Short-Term Strength Training.” *Muscle & Nerve* 35 (1): 78–86. doi:10.1002/mus.20666.

Bobbert, Maarten F., and Gerrit Jan van Ingen Schenau. 1988. “Coordination in Vertical Jumping.” *Journal of Biomechanics* 21 (3): 249–62. doi:10.1016/0021-9290(88)90175-3.

Bobbert, Maarten F., L.J. Richard Casius, and Dinant A. Kistemaker. 2013. “Humans Make Near-Optimal Adjustments of Control to Initial Body Configuration in Vertical Squat Jumping.” *Neuroscience* 237 (May): 232–42. doi:10.1016/j.neuroscience.2013.01.055.

Bonato, P., M.S.S. Heng, J. Gonzalez-Cueto, A. Leardini, J. O’Connor, and S.H. Roy. 2001. “EMG-Based Measures of Fatigue During a Repetitive Squat Exercise.” *IEEE Engineering in Medicine and Biology Magazine* 20 (6): 133–43. doi:10.1109/51.982285.

Bosco, Carmelo, Pekka Luhtanen, and Paavo V. Komi. 1983. “A Simple Method for Measurement of Mechanical Power in Jumping.” *European Journal of Applied Physiology and Occupational Physiology* 50 (2): 273–82.

Bouillard, Killian, Antoine Nordez, Paul W Hodges, Christophe Cornu, and François Hug. 2012. “Evidence of Changes in Load Sharing During Isometric Elbow Flexion with Ramped Torque.” *Journal of Biomechanics* 45 (8): 1424–9. doi:10.1016/j.jbiomech.2012.02.020.

Bowie, W, and G R Cumming. 1971. “Sustained Handgrip-Reproducibility: Effects of Hypoxia.” *Medicine and Science in Sports* 3 (1): 24–31.

Brandon, R., G. Howatson, F. Strachan, and A. M. Hunter. 2015. “Neuromuscular Response Differences to Power Vs Strength Back Squat Exercise in Elite Athletes: EMG, Power, Interpolated Twitch Force.” *Scandinavian Journal of Medicine & Science in Sports* 25 (5):

630–39. doi:10.1111/sms.12289.

Brocherie, Franck, and Grégoire P. Millet. 2018. "'Live High-Train Low' Paradigm: Moving the Debate Forward." *Exercise and Sport Sciences Reviews* 46 (4): 271. doi:10.1249/JES.0000000000000164.

Brocherie, Franck, Olivier Girard, Raphael Faiss, and Gregoire P Millet. 2015. "High-Intensity Intermittent Training in Hypoxia: A Double-Blinded, Placebo-Controlled Field Study in Youth Football Players." *Journal of Strength and Conditioning Research* 29 (1): 226–37. doi:10.1519/JSC.0000000000000590.

Brocherie, Franck, Grégoire P. Millet, and Olivier Girard. 2016. "Psycho-Physiological Responses to Repeated-Sprint Training in Normobaric Hypoxia and Normoxia." *International Journal of Sports Physiology and Performance*, August, 1–25. doi:10.1123/ijspp.2016-0052.

Brzycki, Matt. 1993. "Strength TestingPredicting a One-Rep Max from Reps-to-Fatigue." *Journal of Physical Education, Recreation & Dance* 64 (1): 88–90. doi:10.1080/07303084.1993.10606684.

Buckthorpe, M., R. M. Erskine, G. Fletcher, and J. P. Folland. 2015. "Task-Specific Neural Adaptations to Isoinertial Resistance Training." *Scandinavian Journal of Medicine & Science in Sports* 25 (5): 640–49. doi:10.1111/sms.12292.

Buckthorpe, Matthew W., Ricci Hannah, T.G. Pain, and J. P. Folland. 2012. "Reliability of Neuromuscular Measurements During Explosive Isometric Contractions, with Special Reference to Electromyography Normalization Techniques." *Muscle & Nerve* 46 (4): 566–76. doi:10.1002/mus.23322.

Butterfield, G. E., J. Gates, S. Fleming, G. A. Brooks, J. R. Sutton, and J. T. Reeves. 1992. "Increased Energy Intake Minimizes Weight Loss in Men at High Altitude." *Journal of Applied Physiology (Bethesda, Md.: 1985)* 72 (5): 1741–8. doi:10.1152/jappl.1992.72.5.1741.

Caquelard, F., H. Burnet, F. Tagliarini, E. Cauchy, J. P. Richalet, and Y. Jammes. 2000. "Effects of Prolonged Hypobaric Hypoxia on Human Skeletal Muscle Function and Electromyographic Events." *Clinical Science (London, England: 1979)* 98 (3): 329–37.

Casale, Roberto, Dario Farina, Roberto Merletti, and Alberto Rainoldi. 2004. "Myoelectric Manifestations of Fatigue During Exposure to Hypobaric Hypoxia for 12 Days." *Muscle and Nerve* 30 (5): 618–25. doi:10.1002/mus.20160.

Chimera, Nicole J., Kathleen A. Swanik, C. Buz Swanik, and Stephen J. Straub. 2004. "Effects of Plyometric Training on Muscle-Activation Strategies and Performance in Female Athletes." *Journal of Athletic Training* 39 (1): 24–31.

Christie, Anita, and Gary Kamen. 2010. "Short-Term Training Adaptations in Maximal Motor Unit Firing Rates and Afterhyperpolarization Duration." *Muscle & Nerve* 41 (5): 651–60. doi:10.1002/mus.21539.

Classen, J., J. Liepert, S. P. Wise, M. Hallett, and L. G. Cohen. 1998. "Rapid Plasticity of Human Cortical Movement Representation Induced by Practice." *Journal of Neurophysiology* 79 (2): 1117–23.

Conkin, Johnny, and James H. Wessel. 2008. "Critique of the Equivalent Air Altitude Model." *Aviation, Space, and Environmental Medicine* 79 (10): 975–82.

Coratella, Giuseppe, Marco Beato, Chiara Milanese, Stefano Longo, Eloisa Limonta, Susanna Rampichini, Emiliano Cè, Angela V. Bisconti, Federico Schena, and Fabio Esposito. 2018. "Specific Adaptations in Performance and Muscle Architecture After Weighted Jump-Squat Vs. Body Mass Squat Jump Training in Recreational Soccer Players." *The Journal of Strength & Conditioning Research* 32 (4): 921. doi:10.1519/JSC.0000000000002463.

Cormie, Prue, Grant O. McCaulley, N. Travis Triplett, and Jeffrey M. McBride. 2007. "Optimal Loading for Maximal Power Output During Lower-Body Resistance Exercises." *Medicine and Science in Sports and Exercise* 39 (2): 340–49. doi:10.1249/01.mss.0000246993.71599.bf.

Cormie, Prue, Michael R McGuigan, and Robert U Newton. 2011a. "Developing Maximal

Neuromuscular Power: Part 2 for Improving Maximal Power Production.” *Sports Med*, 22.

Cormie, Prue, Michael R. McGuigan, and Robert U. Newton. 2010. “Adaptations in Athletic Performance After Ballistic Power Versus Strength Training.” *Medicine and Science in Sports and Exercise* 42 (8): 1582–98. doi:10.1249/MSS.0b013e3181d2013a.

———. 2011b. “Developing Maximal Neuromuscular Power: Part 1–Biological Basis of Maximal Power Production.” *Sports Medicine (Auckland, N.Z.)* 41 (1): 17–38. doi:10.2165/11537690-000000000-00000.

Cormie, Prue, Michael R. Mcguigan, and Robert U. Newton. 2010. “Influence of Strength on Magnitude and Mechanisms of Adaptation to Power Training:” *Medicine & Science in Sports & Exercise* 42 (8): 1566–81. doi:10.1249/MSS.0b013e3181cf818d.

Cronin, John, Peter J McNair, and Robert N Marshall. 2001. “Developing Explosive Power: A Comparison of Technique and Training.” *Journal of Science and Medicine in Sport* 4 (1): 59–70. doi:10.1016/S1440-2440(01)80008-6.

Cuk, Ivan, Dragan Mirkov, Aleksandar Nedeljkovic, Milos Kukolj, Dusan Ugarkovic, and Slobodan Jaric. 2016. “ForceVelocity Property of Leg Muscles in Individuals of Different Level of Physical Fitness.” *Sports Biomechanics* 15 (2): 207–19. doi:10.1080/14763141.2016.1159724.

Day, Meghan L., Michael R. McGuigan, Glenn Brice, and Carl Foster. 2004. “Monitoring Exercise Intensity During Resistance Training Using the Session RPE Scale.” *Journal of Strength and Conditioning Research* 18 (2): 353–58. doi:10.1519/R-13113.1.

de Ruiter, C. J., Alex de Korte, Sander Schreven, and Arnold de Haan. 2010. “Leg Dominancy in Relation to Fast Isometric Torque Production and Squat Jump Height.” *European Journal of Applied Physiology* 108 (2): 247–55. doi:10.1007/s00421-009-1209-0.

de Ruiter, C. J., Daniel Van Leeuwen, Arjan Heijblom, Maarten F. Bobbert, and Arnold de Haan. 2006. “Fast Unilateral Isometric Knee Extension Torque Development and Bilateral Jump Height.” *Medicine and Science in Sports and Exercise* 38 (10): 1843–52.

doi:10.1249/01.mss.0000227644.14102.50.

de Ruiter, C. J., Gido Vermeulen, Huub M. Toussaint, and Arnold de Haan. 2007. "Isometric Knee-Extensor Torque Development and Jump Height in Volleyball Players." *Medicine and Science in Sports and Exercise* 39 (8): 1336–46. doi:10.1097/mss.0b013e318063c719.

Degache, Francis, Gabriele Larghi, Raphael Faiss, Olivier Deriaz, and Gregoire Millet. 2012. "Hypobaric Versus Normobaric Hypoxia: Same Effects on Postural Stability?" *High Altitude Medicine & Biology* 13 (1): 40–45. doi:10.1089/ham.2011.1042.

Degens, Hans, J Manuel Sanchez Horneros, and Maria T E Hopman. 2006. "Acute Hypoxia Limits Endurance but Does Not Affect Muscle Contractile Properties." *Muscle & Nerve* 33 (4): 532–7. doi:10.1002/mus.20485.

Del Vecchio, Alessandro Del, Francesco Negro, Francesco Felici, and Dario Farina. 2017. "Associations Between Motor Unit Action Potential Parameters and Surface EMG Features." *Journal of Applied Physiology*, July, jap.00482.2017. doi:10.1152/japplphysiol.00482.2017.

Deldicque, Louise, and Marc Francaux. 2013. "Acute Vs Chronic Hypoxia: What Are the Consequences for Skeletal Muscle Mass?" *Cellular and Molecular Exercise Physiology* 2 (1): 1–23. doi:10.7457/cmep.v2i1.e5.

Delliaux, Stéphane, and Yves Jammes. 2006. "Effects of Hypoxia on Muscle Response to Tendon Vibration in Humans." *Muscle and Nerve* 34 (6): 754–61. doi:10.1002/mus.20633.

Deprettere, Ed F. 1989. *SVD and Signal Processing: Algorithms, Applications and Architectures*. North-Holland Publishing Co.

Desmedt, J. E., and E. Godaux. 1977. "Ballistic Contractions in Man: Characteristic Recruitment Pattern of Single Motor Units of the Tibialis Anterior Muscle." *The Journal of Physiology* 264 (3): 673–93.

Dick, Taylor J. M., and James M. Wakeling. 2017. "Shifting Gears: Dynamic Muscle Shape Changes and Force-Velocity Behavior in the Medial Gastrocnemius." *Journal of Applied*

*Physiology* 123 (6): 1433–42. doi:10.1152/japplphysiol.01050.2016.

Dimitrov, G.V., T.I. Arabadzhiev, J.-Y. Hogrel, and N.A. Dimitrova. 2008. “Simulation Analysis of Interference EMG During Fatiguing Voluntary Contractions. Part II in Amplitude and Spectral Characteristics.” *Journal of Electromyography and Kinesiology* 18 (1): 35–43. doi:10.1016/j.jelekin.2006.07.002.

Dimitrov, George V., Todor I. Arabadzhiev, Katya N. Mileva, Joanna L. Bowtell, Nicola Crichton, and Nonna A. Dimitrova. 2006. “Muscle Fatigue During Dynamic Contractions Assessed by New Spectral Indices:” *Medicine & Science in Sports & Exercise* 38 (11): 1971–9. doi:10.1249/01.mss.0000233794.31659.6d.

Dousset, Erick, Patrick Decherchi, Laurent Grelot, and Yves Jammes. 2001. “Effects of Chronic Hypoxemia on the Afferent Nerve.” *American Journal of Respiratory and Critical Care Medicine* 164: 1476–80. doi:10.1164/rccm2010135.

Dousset, Erick, Jean Guillaume Steinberg, Norbert Balon, and Yves Jammes. 2001. “Effects of Acute Hypoxemia on Force and Surface EMG During Sustained Handgrip.” *Muscle and Nerve* 24 (3): 364–71. doi:10.1002/1097-4598(200103)24:3<364::AID-MUS1007>3.0.CO;2-B.

Doyon, Julien, and Habib Benali. 2005. “Reorganization and Plasticity in the Adult Brain During Learning of Motor Skills.” *Current Opinion in Neurobiology* 15 (2): 161–67. doi:10.1016/j.conb.2005.03.004.

Driss, Tarak, Henry Vandewalle, Jean-Michel Le Chevalier, and Hugues Monod. 2002. “Force-Velocity Relationship on a Cycle Ergometer and Knee-Extensor Strength Indices.” *Canadian Journal of Applied Physiology = Revue Canadienne de Physiologie Appliquee* 27 (3): 250–62.

Duchateau, Jacques, John G Semmler, and R. M. Enoka. 2006. “Training Adaptations in the Behavior of Human Motor Units.” *Journal of Applied Physiology (Bethesda, Md. : 1985)* 101 (6): 1766–75. doi:10.1152/japplphysiol.00543.2006.

D’Hulst, Gommaar, and Louise Deldicque. 2017. “Last Word on Viewpoint: Human Skeletal

Muscle Wasting in Hypoxia: A Matter of Hypoxic Dose?” *Journal of Applied Physiology* 122 (2): 412–13. doi:10.1152/japplphysiol.01082.2016.

Earp, Jacob E, Robert U Newton, Prue Cormie, and Anthony J Blazevich. 2017. “The Influence of External Load on Quadriceps Muscle and Tendon Dynamics During Jumping:” *Medicine & Science in Sports & Exercise*, June, 1. doi:10.1249/MSS.0000000000001361.

Earp, Jacob E., Robert U. Newton, Prue Cormie, and Anthony J. Blazevich. 2015. “Inhomogeneous Quadriceps Femoris Hypertrophy in Response to Strength and Power Training:” *Medicine & Science in Sports & Exercise* 47 (11): 2389–97. doi:10.1249/MSS.0000000000000669.

———. 2016. “Faster Movement Speed Results in Greater Tendon Strain During the Loaded Squat Exercise.” *Frontiers in Physiology* 7 (August). doi:10.3389/fphys.2016.00366.

Eiken, O, and P a Tesch. 1984. “Effects of Hyperoxia and Hypoxia on Dynamic and Sustained Static Performance of the Human Quadriceps Muscle.” *Acta Physiologica Scandinavica* 122 (4): 629–33. doi:10.1111/j.1748-1716.1984.tb07553.x.

Enoka, R. M. 1995. “Mechanisms of Muscle Fatigue: Central Factors and Task Dependency.” *Journal of Electromyography and Kinesiology* 5 (3): 141–49.

Enoka, R. M., and Jacques Duchateau. 2015. “Inappropriate Interpretation of Surface EMG Signals and Muscle Fiber Characteristics Impedes Understanding of the Control of Neuromuscular Function.” *Journal of Applied Physiology (Bethesda, Md.: 1985)* 119 (12): 1516–8. doi:10.1152/japplphysiol.00280.2015.

———. 2016. “Translating Fatigue to Human Performance.” *Medicine & Science in Sports & Exercise* 48 (11): 2228–38. doi:10.1249/MSS.0000000000000929.

———. 2017. “Rate Coding and the Control of Muscle Force.” *Cold Spring Harbor Perspectives in Medicine*, March, a029702. doi:10.1101/cshperspect.a029702.

Erskine, Robert M., David A. Jones, Alun G. Williams, Claire E. Stewart, and Hans Degens.

2010. “Inter-Individual Variability in the Adaptation of Human Muscle Specific Tension to Progressive Resistance Training.” *European Journal of Applied Physiology* 110 (6): 1117–25. doi:10.1007/s00421-010-1601-9.

Esposito, Fabio, Claudio Orizio, Giovanni Parrinello, and Arsenio Veicsteinas. 2003. “Chronic Hypobaric Hypoxia Does Not Affect Electro-Mechanical Muscle Activities During Sustained Maximal Isometric Contractions.” *European Journal of Applied Physiology* 90 (3-4): 337–43. doi:10.1007/s00421-003-0922-3.

Evans, W. O., and C. F. Consolazio. 1967. “Effects of High Altitude on Performance of Three Different Types of Work.” *Perceptual and Motor Skills* 25 (1): 41–50. doi:10.2466/pms.1967.25.1.41.

Faiss, Raphael, Vincent Pialoux, Claudio Sartori, Camille Faes, Olivier Dériaz, and Grégoire P. Millet. 2013. “Ventilation, Oxidative Stress, and Nitric Oxide in Hypobaric Versus Normobaric Hypoxia.” *Medicine and Science in Sports and Exercise* 45 (2): 253–60. doi:10.1249/MSS.0b013e31826d5aa2.

Faiss, Raphaël, Olivier Girard, and Grégoire P Millet. 2013. “Advancing Hypoxic Training in Team Sports: From Intermittent Hypoxic Training to Repeated Sprint Training in Hypoxia.” *British Journal of Sports Medicine* 47 Suppl 1: i45–50. doi:10.1136/bjsports-2013-092741.

Farina, Dario. 2006. “Interpretation of the Surface Electromyogram in Dynamic Contractions.” *Exercise and Sport Sciences Reviews* 34 (3): 121–27.

Farina, Dario, Francesco Negro, and Jakob Lund Dideriksen. 2014. “The Effective Neural Drive to Muscles Is the Common Synaptic Input to Motor Neurons: Effective Neural Drive to Muscles.” *The Journal of Physiology* 592 (16): 3427–41. doi:10.1113/jphysiol.2014.273581.

Farina, Dario, Francesco Negro, Silvia Muceli, and R. M. Enoka. 2016. “Principles of Motor Unit Physiology Evolve with Advances in Technology.” *Physiology* 31 (2): 83–94. doi:10.1152/physiol.00040.2015.

Farrell, P. A., J. J. Joyner, and V. J. Caiozzo. 2012. *ACSM’s Advanced Exercise Physiology.*

Second edition. Philadelphia : Wolters Kluwer Health/Lippincott Williams & Wilkins.

Felici, F., A. Rosponi, P. Sbriccoli, M. Scarcia, I. Bazzucchi, and M. Iannattone. 2001. “Effect of Human Exposure to Altitude on Muscle Endurance During Isometric Contractions.” *European Journal of Applied Physiology* 85 (6): 507–12. doi:10.1007/s004210100488.

Feriche, Belén, Amador García-Ramos, Carmen Calderón-Soto, Franchek Drobnic, Juan G. Bonitch- Góngora, Pedro a. Galilea, Joan Riera, and Paulino Padial. 2014. “Effect of Acute Exposure to Moderate Altitude on Muscle Power: Hypobaric Hypoxia Vs. Normobaric Hypoxia.” *PLoS ONE* 9 (12): e114072–e114072. doi:10.1371/journal.pone.0114072.

Feriche, Belén, Amador García-Ramos, Antonio J. Morales-Artacho, and P. Padial. 2017. “Resistance Training Using Different Hypoxic Training Strategies: A Basis for Hypertrophy and Muscle Power Development.” *Sports Medicine - Open* 3. doi:10.1186/s40798-017-0078-z.

Fernandez del Olmo, Miguel, Pedro Reimunde, Oscar Viana, Rafael Martin Acero, and Javier Cudeiro. 2006. “Chronic Neural Adaptation Induced by Long-Term Resistance Training in Humans.” *European Journal of Applied Physiology* 96 (6): 722–28. doi:10.1007/s00421-006-0153-5.

Ferretti, G., H. Hauser, and P. E. di Prampero. 1990. “Maximal Muscular Power Before and After Exposure to Chronic Hypoxia.” *International Journal of Sports Medicine* 11 Suppl 1 (February): S31–34. doi:10.1055/s-2007-1024851.

Finn, Harrison T., Simon C. Gandevia, and Janet L. Taylor. 2018. “Differences in Muscle Performance During Fatigue May Explain the Differences in Motoneurone Excitability Between Acute and Chronic Hypoxia: Letters.” *The Journal of Physiology* 596 (15): 3425–5. doi:10.1113/JP275816.

Folland, J. P., and Alun G. Williams. 2007. “The Adaptations to Strength Training : Morphological and Neurological Contributions to Increased Strength.” *Sports Medicine (Auckland, N.Z.)* 37 (2): 145–68.

Folland, J. P., M W Buckthorpe, and R Hannah. 2014. “Human Capacity for Explosive

Force Production: Neural and Contractile Determinants." *Scandinavian Journal of Medicine & Science in Sports* 24 (6): 894–906. doi:10.1111/sms.12131.

Folland, J. P., C. S. Irish, J. C. Roberts, J. E. Tarr, and D. A. Jones. 2002. "Fatigue Is Not a Necessary Stimulus for Strength Gains During Resistance Training." *British Journal of Sports Medicine* 36 (5): 370–73. doi:10.1136/bjsm.36.5.370.

Friedmann, B., R. Kinscherf, S. Borisch, G. Richter, P. Bärtsch, and R. Billeter. 2003. "Effects of Low-Resistance/High-Repetition Strength Training in Hypoxia on Muscle Structure and Gene Expression." *Pflugers Archiv European Journal of Physiology* 446 (6): 742–51. doi:10.1007/s00424-003-1133-9.

Fulco, C S, S F Lewis, P N Frykman, R Boushel, S Smith, E a Harman, a Cymerman, and K B Pandolf. 1996. "Muscle Fatigue and Exhaustion During Dynamic Leg Exercise in Normoxia and Hypobaric Hypoxia." *Journal of Applied Physiology (Bethesda, Md. : 1985)* 81 (5): 1891–1900.

Fulco, C. S., A. Cymerman, S. R. Muza, P. B. Rock, K. B. Pandolf, and S. F. Lewis. 1994. "Adductor Pollicis Muscle Fatigue During Acute and Chronic Altitude Exposure and Return to Sea Level." *Journal of Applied Physiology (Bethesda, Md.: 1985)* 77 (1): 179–83. doi:10.1152/jappl.1994.77.1.179.

Fulco, C. S., P. B. Rock, and A. Cymerman. 1998. "Maximal and Submaximal Exercise Performance at Altitude." *Aviation, Space, and Environmental Medicine* 69 (8): 793–801.

García-Ramos, Amador, Slobodan Jaric, Paulino Padial, and Belén Feriche. 2016. "Force-Velocity Relationship of Upper Body Muscles: Traditional Versus Ballistic Bench Press." *Journal of Applied Biomechanics* 32 (2): 178–85. doi:10.1123/jab.2015-0162.

García-Ramos, Amador, Slobodan Jaric, Alejandro Pérez-Castilla, Paulino Padial, and Belén Feriche. 2017. "Reliability and Magnitude of Mechanical Variables Assessed from Unconstrained and Constrained Loaded Countermovement Jumps." *Sports Biomechanics* 16 (4):

514–26. doi:10.1080/14763141.2016.1246598.

García-Ramos, Amador, Paulino Padial, G. Gregory Haff, Javier Argüelles-Cienfuegos, Miguel García-Ramos, Javier Conde-Pipó, and Belén Feriche. 2015. "Effect of Different Interrepetition Rest Periods on Barbell Velocity Loss During the Ballistic Bench Press Exercise." *Journal of Strength and Conditioning Research* 29 (9): 2388–96. doi:10.1519/JSC.0000000000000891.

García-Ramos, Amador, Igor Štirn, Paulino Padial, Javier Argüelles-Cienfuegos, Blanca De la Fuente, Vojko Strojnik, and Belén Feriche. 2016. "The Maximal Mechanical Capabilities of Leg Extensors Muscles to Generate Velocity and Power Improve at Altitude." *Journal of Strength and Conditioning Research*, August, 1. doi:10.1519/JSC.0000000000001592.

García-Ramos, Amador, Alejandro Torrejón, Belén Feriche, Antonio J. Morales-Artacho, Alejandro Pérez-Castilla, P. Padial, and Guy Gregory Haff. 2017. "Prediction of the Maximum Number of Repetitions and Repetitions in Reserve from Barbell Velocity." *International Journal of Sports Physiology and Performance*, 1–23. doi:10.1123/ijspp.2017-0302.

Gardiner, P., Y. Dai, and C. J. Heckman. 2006. "Effects of Exercise Training on $\alpha$-Motoneurons." *Journal of Applied Physiology* 101 (4): 1228–36. doi:10.1152/japplphysiol.00482.2006.

Garfinkel, S., and E. Cafarelli. 1992. "Relative Changes in Maximal Force, EMG, and Muscle Cross-Sectional Area After Isometric Training." *Medicine and Science in Sports and Exercise* 24 (11): 1220–7.

Garner, Scott, John R Sutton, Richard L Burse, Alan J McComas, Allen Cymerman, and Charles S Houston. 1991. "Operation Everest II: Neuromuscular Performance Under Conditions of Extreme Simulated Altitude." *Journal of Applied Physiology* 68 (3): 1167–72.

Girard, O., F. Brocherie, and G. P. Millet. 2013. "On the Use of Mobile Inflatable Hypoxic Marquees for Sport-Specific Altitude Training in Team Sports." *British Journal of Sports Medicine* 47 (Suppl_1): i121–i123. doi:10.1136/bjsports-2013-092794.

Girard, Olivier, Franck Brocherie, and Grégoire P. Millet. 2017. "Effects of Altitude/Hypoxia on Single- and Multiple-Sprint Performance: A Comprehensive Review." *Sports Medicine* 47 (10): 1931–49. doi:10.1007/s40279-017-0733-z.

Girman, Julia C., Margaret T. Jones, Tracey D. Matthews, and Richard J. Wood. 2014. "Acute Effects of a Cluster-Set Protocol on Hormonal, Metabolic and Performance Measures in Resistance-Trained Males." *European Journal of Sport Science* 14 (2): 151–59. doi:10.1080/17461391.2013.775351.

Giroux, Caroline, Ga??l Guilhem, Antoine Couturier, Didier Chollet, and Giuseppe Rabita. 2015. "Is Muscle Coordination Affected by Loading Condition in Ballistic Movements?" *Journal of Electromyography and Kinesiology* 25 (1): 69–76. doi:10.1016/j.jelekin.2014.10.014.

Giroux, Caroline, Giuseppe Rabita, Didier Chollet, and Gaël Guilhem. 2016. "Optimal Balance Between Force and Velocity Differs Among World-Class Athletes." *Journal of Applied Biomechanics* 32 (1): 59–68. doi:10.1123/jab.2015-0070.

Glaser, Vojko, and Ales Holobar. 2018. "Motor Unit Identification from High-Density Surface Electromyograms in Repeated Dynamic Muscle Contractions." *IEEE Transactions on Neural Systems and Rehabilitation Engineering: A Publication of the IEEE Engineering in Medicine and Biology Society*, December. doi:10.1109/TNSRE.2018.2885283.

González-Badillo, J. J., and L. Sánchez-Medina. 2010. "Movement Velocity as a Measure of Loading Intensity in Resistance Training." *International Journal of Sports Medicine* 31 (05): 347–52. doi:10.1055/s-0030-1248333.

González-Badillo, Juan José, Juan Manuel Yañez-García, Ricardo Mora-Custodio, and David Rodríguez-Rosell. 2017. "Velocity Loss as a Variable for Monitoring Resistance Exercise." *International Journal of Sports Medicine* 38 (03): 217–25. doi:10.1055/s-0042-120324.

González-Hernádez, J. M., A. García-Ramos, F. Capelo-Ramírez, A. Castaño-Zambudio, G. Marquez, D. Boullosa, and P. Jiménez-Reyes. 2017. "Mechanical, Metabolic, and Perceptual Acute Responses to Different Set Configurations in Full Squat." *Journal of Strength and*

*Conditioning Research*, July. doi:10.1519/JSC.0000000000002117.

González-Izal, M., Deborah Falla, Mikel Izquierdo, and Dario Farina. 2010. "Predicting Force Loss During Dynamic Fatiguing Exercises from Non-Linear Mapping of Features of the Surface Electromyogram." *Journal of Neuroscience Methods* 190 (2): 271–78. doi:10.1016/j.jneumeth.2010.05.003.

González-Izal, M., a. Malanda, I. Navarro-Amézqueta, E. Gorostiaga, F. Mallor, J. Ibañez, and M. Izquierdo. 2010. "EMG Spectral Indices and Muscle Power Fatigue During Dynamic Contractions." *Journal of Electromyography and Kinesiology* 20 (2): 233–40. doi:10.1016/j.jelekin.2009.03.011.

González-Izal, M., I Rodríguez-Carreño, A Malanda, F Mallor-Giménez, I Navarro-Amézqueta, E. Gorostiaga, and M Izquierdo. 2010. "sEMG Wavelet-Based Indices Predicts Muscle Power Loss During Dynamic Contractions." *Journal of Electromyography and Kinesiology : Official Journal of the International Society of Electrophysiological Kinesiology* 20 (6): 1097–1106. doi:10.1016/j.jelekin.2010.05.010.

Goodall, Stuart. 2017. "The Acclimatised Spinal Cord: Perspectives." *The Journal of Physiology*, December. doi:10.1113/JP275552.

Goodall, Stuart, E.Z. Ross, D. Phillips, and L.M. Romer. 2011. "Effect of Graded Hypoxia on Supraspinal Contributions to Fatigue." *Journal of Applied Physiology* 60 (1): 87–87. doi:10.7600/jspfsm.60.87.

Goodall, Stuart, Rosie Twomey, and Markus Amann. 2014. "Acute and Chronic Hypoxia: Implications for Cerebral Function and Exercise Tolerance." *Fatigue: Biomedicine, Health & Behavior* 2 (2): 73–92. doi:10.1080/21641846.2014.909963.

Gorostiaga, E., Ion Navarro-Amézqueta, M. González-Izal, Armando Malanda, Cristina Granados, Javier Ibáñez, Igor Setuain, and Mikel Izquierdo. 2012. "Blood Lactate and sEMG at Different Knee Angles During Fatiguing Leg Press Exercise." *European Journal of*

*Applied Physiology* 112 (4): 1349–58. doi:10.1007/s00421-011-2090-1.

Grocott, Michael P, D Martin, D Levett, R McMorrow, J Windsor, and H Montgomery. 2009. “Arterial Blood Gases and Oxygen Content in Climbers on Mount Everest.” *The New England Journal of Medicine* 360: 140–49.

Haff, G Gregory, Ryan T Hobbs, Erin E Haff, William A Sands, Kyle C Pierce, and Michael H Stone. 2008. “Cluster Training: A Novel Method for Introducing Training Program Variation:” *Strength and Conditioning Journal* 30 (1): 67–76. doi:10.1519/SSC.0b013e31816383e1.

Haff, G. Gregory, and Sophia Nimphius. 2012. “Training Principles for Power.” *Strength & Conditioning Journal* 34 (6): 2–12.

Haff, G. Gregory, Michael Stone, Harold S. O’Bryant, Everett Harman, Chris Dinan, Robert Johnson, and Ki-Hoon Han. 1997. “Force-Time Dependent Characteristics of Dynamic and Isometric Muscle Actions:” *Journal of Strength and Conditioning Research* 11 (4): 269–72. doi:10.1519/00124278-199711000-00014.

Hamlin, Michael J., Will G. Hopkins, and Stephen C. Hollings. 2015. “Effects of Altitude on Performance of Elite Track-and-Field Athletes.” *International Journal of Sports Physiology and Performance* 10 (7): 881–87. doi:10.1123/ijspp.2014-0261.

Hansen, J., and M. Sander. 2002. “Sympathetic Neural Overactivity in Healthy Humans After Prolonged Exposure to Hypobaric Hypoxia.” *The Journal of Physiology* 546 (3): 921–29. doi:10.1113/jphysiol.2002.031765.

Hansen, Keir T., John B. Cronin, and Michael J. Newton. 2011. “The Effect of Cluster Loading on Force, Velocity, and Power During Ballistic Jump Squat Training.” *International Journal of Sports Physiology and Performance* 6 (4): 455–68.

Hansen, Keir T., John B. Cronin, Stuart L. Pickering, and Michael J. Newton. 2011. “Does Cluster Loading Enhance Lower Body Power Development in Preseason Preparation of Elite Rugby Union Players?” *Journal of Strength and Conditioning Research* 25 (8): 2118–26.

doi:10.1519/JSC.0b013e318220b6a3.

Hardee, Justin P., N. Travis Triplett, Alan C. Utter, Kevin A. Zwetsloot, and Jeffrey M. Mcbride. 2012. "Effect of Interrepetition Rest on Power Output in the Power Clean." *Journal of Strength and Conditioning Research* 26 (4): 883–89. doi:10.1519/JSC.0b013e3182474370.

Häkkinen, K., M. Alén, and P. V. Komi. 1985. "Changes in Isometric Force- and Relaxation-Time, Electromyographic and Muscle Fibre Characteristics of Human Skeletal Muscle During Strength Training and Detraining." *Acta Physiologica Scandinavica* 125 (4): 573–85. doi:10.1111/j.1748-1716.1985.tb07760.x.

Henneman, E. 1957. "Relation Between Size of Neurons and Their Susceptibility to Discharge." *Science (New York, N.Y.)* 126 (3287): 1345–7.

Hermens, H. J., B. Freriks, C. Disselhorst-Klug, and G. Rau. 2000. "Development of Recommendations for SEMG Sensors and Sensor Placement Procedures." *Journal of Electromyography and Kinesiology* 10 (5): 361–74.

Ho, Jen-Yu, Tai-Yu Kuo, Kuan-Lin Liu, Xiang-Yi Dong, and Kang Tung. 2014. "Combining Normobaric Hypoxia with Short-Term Resistance Training Has No Additive Beneficial Effect on Muscular Performance and Body Composition." *Journal of Strength and Conditioning Research* 28 (4): 935–41. doi:10.1519/JSC.0000000000000289.

Hoppeler, Hans, and Michael Vogt. 2001. "Muscle Tissue Adaptations to Hypoxia." *The Journal of Experimental Biology* 204: 3133–9.

Iglesias-Soler, Eliseo, Miguel Fernández-del-Olmo, Xián Mayo, Juan Fariñas, Dan Río-Rodríguez, Eduardo Carballeira, Elvis A. Carnero, et al. 2016. "Changes in the Force-Velocity Mechanical Profile After Short Resistance Training Programmes Differing in Set Configurations." *Journal of Applied Biomechanics*, December, 1–27. doi:10.1123/jab.2016-0181.

Iglesias-Soler, Eliseo, Xián Mayo, Dan Río-Rodríguez, Eduardo Carballeira, Juan Fariñas, and Miguel Fernández-Del-Olmo. 2016. "Inter-Repetition Rest Training and Traditional Set

Configuration Produce Similar Strength Gains Without Cortical Adaptations." *Journal of Sports Sciences* 34 (15): 1473–84. doi:10.1080/02640414.2015.1119299.

Inness, Mathew W. H., François Billaut, Emily J. Walker, Aaron C. Petersen, Alice J. Sweeting, and Robert J. Aughey. 2016. "Heavy Resistance Training in Hypoxia Enhances 1rm Squat Performance." *Frontiers in Physiology* 7 (November). doi:10.3389/fphys.2016.00502.

Izquierdo, M., J. J. González-Badillo, K. Häkkinen, J. Ibáñez, W. J. Kraemer, A. Altadill, J. Eslava, and E. Gorostiaga. 2006. "Effect of Loading on Unintentional Lifting Velocity Declines During Single Sets of Repetitions to Failure During Upper and Lower Extremity Muscle Actions." *International Journal of Sports Medicine* 27 (9): 718–24. doi:10.1055/s-2005-872825.

Izquierdo, M., J. Ibañez, J. Calbet, M. González-Izal, I. Navarro-Amézqueta, C. Granados, A. Malanda, et al. 2009. "Neuromuscular Fatigue After Resistance Training." *International Journal of Sports Medicine* 30 (08): 614–23. doi:10.1055/s-0029-1214379.

Jakobsen, J. R., A. L. Mackey, A. B. Knudsen, M. Koch, M. Kjaer, and M. R. Krogsgaard. 2016. "Composition and Adaptation of Human Myotendinous Junction and Neighboring Muscle Fibers to Heavy Resistance Training." *Scandinavian Journal of Medicine & Science in Sports*, October. doi:10.1111/sms.12794.

James, L. P., G. Gregory Haff, V. G. Kelly, M. J. Connick, B. W. Hoffman, and E. M. Beckman. 2018. "The Impact of Strength Level on Adaptations to Combined Weightlifting, Plyometric, and Ballistic Training." *Scandinavian Journal of Medicine & Science in Sports*, March. doi:10.1111/sms.13045.

Jaric, S. 2015. "Force-Velocity Relationship of Muscles Performing Multi-Joint Maximum Performance Tasks." *International Journal of Sports Medicine* 36 (09): 699–704. doi:10.1055/s-0035-1547283.

Jensen, Jesper Lundbye, Peter C. D. Marstrand, and Jens B. Nielsen. 2005. "Motor Skill Training and Strength Training Are Associated with Different Plastic Changes in the Central

Nervous System." *Journal of Applied Physiology (Bethesda, Md.: 1985)* 99 (4): 1558–68. doi:10.1152/japplphysiol.01408.2004.

Jiménez-Reyes, Pedro, Pierre Samozino, Matt Brughelli, and Jean-Benoît Morin. 2017. "Effectiveness of an Individualized Training Based on Force-Velocity Profiling During Jumping." *Frontiers in Physiology* 7 (January). doi:10.3389/fphys.2016.00677.

Jokl, E., P. Jokl, and D. C. Seaton. 1969. "Effect of Altitude Upon 1968 Olympic Games Running Performances." *International Journal of Biometeorology* 13 (3-4): 309–11. doi:10.1007/BF01553038.

Juel, C., C. Lundby, M. Sander, J. a. L. Calbet, and G. van Hall. 2003. "Human Skeletal Muscle and Erythrocyte Proteins Involved in Acid-Base Homeostasis: Adaptations to Chronic Hypoxia." *The Journal of Physiology* 548 (Pt 2): 639–48. doi:10.1113/jphysiol.2002.035899.

Kamen, G., and C. A. Knight. 2004. "Training-Related Adaptations in Motor Unit Discharge Rate in Young and Older Adults." *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences* 59 (12): 1334–8. doi:10.1093/gerona/59.12.1334.

Katayama, Keisho, Markus Amann, David F Pegelow, Anthony J Jacques, and Jerome a Dempsey. 2007. "Effect of Arterial Oxygenation on Quadriceps Fatigability During Isolated Muscle Exercise." *American Journal of Physiology. Regulatory, Integrative and Comparative Physiology* 292 (3): R1279–86. doi:10.1152/ajpregu.00554.2006.

Katayama, Keisho, Koji Ishida, Erika Iwamoto, Motoyuki Iemitsu, Teruhiko Koike, and Mitsuru Saito. 2011. "Hypoxia Augments Muscle Sympathetic Neural Response to Leg Cycling." *American Journal of Physiology. Regulatory, Integrative and Comparative Physiology* 301 (2): R456–64. doi:10.1152/ajpregu.00119.2011.

Kayser, B., R. Bokenkamp, and T. Binzoni. 1993. "Alpha-Motoneuron Excitability at High Altitude." *European Journal of Applied Physiology and Occupational Physiology* 66 (1): 1–4. doi:10.1007/BF00863391.

Kayser, Bengt, Marco Narici, Tiziano Binzoni, Bruno Grassi, and Paolo Cerretelli. 1994.

"Fatigue and Exhaustion in Chronic Hypobaric Hypoxia: Influence of Exercising Muscle Mass." *Journal of Applied Physiology.*

Khamoui, Andy V., Lee E. Brown, Diamond Nguyen, Brandon P. Uribe, Jared W. Coburn, Guillermo J. Noffal, and Tai Tran. 2011. "Relationship Between Force-Time and Velocity-Time Characteristics of Dynamic and Isometric Muscle Actions." *The Journal of Strength & Conditioning Research* 25 (1): 198–204.

Kidgell, Dawson J., Daniel R. Bonanno, Ashlyn K. Frazer, Glyn Howatson, and Alan J. Pearce. 2017. "Corticospinal Responses Following Strength Training: A Systematic Review and Meta-Analysis." *European Journal of Neuroscience* 46 (11): 2648–61. doi:10.1111/ejn.13710.

Kjaer, Michael. 2004. "Role of Extracellular Matrix in Adaptation of Tendon and Skeletal Muscle to Mechanical Loading." *Physiological Reviews* 84 (2): 649–98. doi:10.1152/physrev.00031.2003.

Klinge, Klaus, S. Peter Magnusson, Erik B. Simonsen, P. Aagaard, Klaus Klausen, and Michael Kjaer. 1997. "The Effect of Strength and Flexibility Training on Skeletal Muscle Electromyographic Activity, Stiffness, and Viscoelastic Stress Relaxation Response." *The American Journal of Sports Medicine* 25 (5): 710–16. doi:10.1177/036354659702500522.

Knight, C. A., and G. Kamen. 2001. "Adaptations in Muscular Activation of the Knee Extensor Muscles with Strength Training in Young and Older Adults." *Journal of Electromyography and Kinesiology: Official Journal of the International Society of Electrophysiological Kinesiology* 11 (6): 405–12.

Komi, Paavo V. 2000. "Stretch-Shortening Cycle: A Powerful Model to Study Normal and Fatigued Muscle." *Journal of Biomechanics* 33 (10): 1197–1206. doi:10.1016/S0021-9290(00)00064-6.

Komi, Paavo V., and Caroline Nicol. 2010. "Stretch-Shortening Cycle of Muscle Function." In *Neuromuscular Aspects of Sport Performance*, edited by Paavo V. Komi, 15–31. Oxford, UK: Wiley-Blackwell. doi:10.1002/9781444324822.ch2.

Kon, Michihiro, Tatsuaki Ikeda, Toshiyuki Homma, Takayuki Akimoto, Yasuhiro Suzuki, and Takashi Kawahara. 2010. "Effects of Acute Hypoxia on Metabolic and Hormonal Responses to Resistance Exercise." *Medicine and Science in Sports and Exercise* 42 (7): 1279–85. doi:10.1249/MSS.0b013e3181ce61a5.

Kon, Michihiro, Tatsuaki Ikeda, Toshiyuki Homma, and Yasuhiro Suzuki. 2012. "Effects of Low-Intensity Resistance Exercise Under Acute Systemic Hypoxia on Hormonal Responses." *Journal of Strength and Conditioning Research* 26 (3): 611–17. doi:10.1519/JSC.0b013e3182281c69.

Kon, Michihiro, Nao Ohiwa, Akiko Honda, Takeo Matsubayashi, Tatsuaki Ikeda, Takayuki Akimoto, Yasuhiro Suzuki, Yuichi Hirano, and Aaron P Russell. 2014. "Effects of Systemic Hypoxia on Human Muscular Adaptations to Resistance Exercise Training." *Physiological Reports* 2 (6): 1–13. doi:10.14814/phy2.12033.

Kraft, Justin A., James M. Green, and Kyle R. Thompson. 2014. "Session Ratings of Perceived Exertion Responses During Resistance Training Bouts Equated for Total Work but Differing in Work Rate." *Journal of Strength and Conditioning Research* 28 (2): 540–45. doi:10.1519/JSC.0b013e31829b569c.

Kumagai, K., T. Abe, W. F. Brechue, T. Ryushi, S. Takano, and M. Mizuno. 2000. "Sprint Performance Is Related to Muscle Fascicle Length in Male 100-M Sprinters." *Journal of Applied Physiology (Bethesda, Md.: 1985)* 88 (3): 811–16. doi:10.1152/jappl.2000.88.3.811.

Kurobe, Kazumichi, Zhong Huang, Masato Nishiwaki, Masayoshi Yamamoto, Hiroaki Kanehisa, and Futoshi Ogita. 2015. "Effects of Resistance Training Under Hypoxic Conditions on Muscle Hypertrophy and Strength." *Clinical Physiology and Functional Imaging* 35 (3): 197–202. doi:10.1111/cpf.12147.

Lawrence, Michael A. 2016. "Ez: Easy Analysis and Visualization of Factorial Experiments."

Lawton, T., J. Cronin, E. Drinkwater, R. Lindsell, and D. Pyne. 2004. "The Effect of

Continuous Repetition Training and Intra-Set Rest Training on Bench Press Strength and Power.” *The Journal of Sports Medicine and Physical Fitness* 44 (4): 361–67.

Leissner, Kay B., and Feroze U. Mahmood. 2009. “Physiology and Pathophysiology at High Altitude: Considerations for the Anesthesiologist.” *Journal of Anesthesia* 23 (4): 543–53. doi:10.1007/s00540-009-0787-7.

Lieber, R. L., and J. Fridén. 2000. “Functional and Clinical Significance of Skeletal Muscle Architecture.” *Muscle & Nerve* 23 (11): 1647–66.

Linnamo, V., K. Häkkinen, and P. V. Komi. 1997. “Neuromuscular Fatigue and Recovery in Maximal Compared to Explosive Strength Loading.” *European Journal of Applied Physiology and Occupational Physiology* 77 (1): 176–81.

Linnamo, V., R. U. Newton, K. Häkkinen, P. V. Komi, A. Davie, M. McGuigan, and T. Triplett-McBride. 2000. “Neuromuscular Responses to Explosive and Heavy Resistance Loading.” *Journal of Electromyography and Kinesiology* 10 (6): 417–24.

Linthorne, Nicholas P. 2001. “Analysis of Standing Vertical Jumps Using a Force Platform.” *American Journal of Physics* 69 (11): 1198–1204. doi:10.1119/1.1397460.

Lockhart, Catriona, Brendan R. Scott, Bradley Thoseby, and Ben J. Dascombe. 2018. “Acute Effects of Interset Rest Duration on Physiological and Perceptual Responses to Resistance Exercise in Hypoxia.” *Journal of Strength and Conditioning Research*, July. doi:10.1519/JSC.0000000000002755.

MacDougall, J D, H J Green, J R Sutton, G Coates, A Cymerman, P Young, and C S Houston. 1991. “Operation Everest II: Structural Adaptations in Skeletal Muscle in Response to Extreme Simulated Altitude.” *Acta Physiologica Scandinavica* 142 (3): 421–27. doi:10.1111/j.1748-1716.1991.tb09176.x.

Maffiuletti, Nicola A., P. Aagaard, Anthony J. Blazevich, Jonathan Folland, N. A. Tillin, and Jacques Duchateau. 2016. “Rate of Force Development: Physiological and Methodological Considerations.” *European Journal of Applied Physiology* 116 (6): 1091–1116.

doi:10.1007/s00421-016-3346-6.

Magnusson, S. Peter, and Michael Kjaer. 2018. "The Impact of Loading, Unloading, Ageing and Injury on the Human Tendon: Exercise and Tendon." *The Journal of Physiology*, July. doi:10.1113/JP275450.

Magnusson, S. Peter, Marco V. Narici, Constantinos N. Maganaris, and Michael Kjaer. 2008. "Human Tendon Behaviour and Adaptation, in Vivo." *The Journal of Physiology* 586 (1): 71–81. doi:10.1113/jphysiol.2007.139105.

Maluf, Katrina S., Minoru Shinohara, Jennifer L. Stephenson, and R. M. Enoka. 2005. "Muscle Activation and Time to Task Failure Differ with Load Type and Contraction Intensity for a Human Hand Muscle." *Experimental Brain Research* 167 (2): 165–77. doi:10.1007/s00221-005-0017-y.

Mandic, Radivoj, Sasa Jakovljevic, and Slobodan Jaric. 2015. "Effects of Countermovement Depth on Kinematic and Kinetic Patterns of Maximum Vertical Jumps." *Journal of Electromyography and Kinesiology* 25 (2): 265–72. doi:10.1016/j.jelekin.2014.11.001.

Manimmanakorn, A., Michael J Hamlin, Jenny J Ross, Robert Taylor, and N. Manimmanakorn. 2013. "Effects of Low-Load Resistance Training Combined with Blood Flow Restriction or Hypoxia on Muscle Function and Performance in Netball Athletes." *Journal of Science and Medicine in Sport / Sports Medicine Australia* 16 (4): 337–42. doi:10.1016/j.jsams.2012.08.009.

Manimmanakorn, A., N. Manimmanakorn, Robert Taylor, Nick Draper, Francois Billaut, Jeremy P Shearman, and Michael J Hamlin. 2013. "Effects of Resistance Training Combined with Vascular Occlusion or Hypoxia on Neuromuscular Function in Athletes." *European Journal of Applied Physiology* 113 (7): 1767–74. doi:10.1007/s00421-013-2605-z.

Marillier, Mathieu, Pierrick J. Arnal, Thibault Le Roux Mallouf, Thomas Rupp, Guillaume Y. Millet, and Samuel Verges. 2017. "Effects of High-Altitude Exposure on Supraspinal Fatigue and Corticospinal Excitability and Inhibition." *European Journal of Applied Physiology*, June. doi:10.1007/s00421-017-3669-y.

Martinez Valdes, Eduardo, Francesco Negro, Deborah Falla, Alessandro Marco De Nunzio, and Dario Farina. 2018. “Surface EMG Amplitude Does Not Identify Differences in Neural Drive to Synergistic Muscles.” *Journal of Applied Physiology (Bethesda, Md.: 1985)*, February. doi:10.1152/japplphysiol.01115.2017.

McGuigan, Michael R., and Jason B. Winchester. 2008. “The Relationship Between Isometric and Dynamic Strength in College Football Players.” *J Sports Sci Med* 7 (1): 101–5.

McGuigan, Michael R., Alison D. Egan, and Carl Foster. 2004. “Salivary Cortisol Responses and Perceived Exertion During High Intensity and Low Intensity Bouts of Resistance Exercise.” *Journal of Sports Science & Medicine* 3 (1): 8–15.

McMahon, John J., Timothy J. Suchomel, Jason P. Lake, and Paul Comfort. 2018. “Understanding the Key Phases of the Countermovement Jump Force-Time Curve:” *Strength and Conditioning Journal*, January, 1. doi:10.1519/SSC.0000000000000375.

McMaster, Daniel Travis, Nicholas Gill, John Cronin, and Michael McGuigan. 2014. “A Brief Review of Strength and Ballistic Assessment Methodologies in Sport.” *Sports Medicine* 44 (5): 603–23. doi:10.1007/s40279-014-0145-2.

Merletti, R., L. R. Lo Conte, and C. Orizio. 1991. “Indices of Muscle Fatigue.” *Journal of Electromyography and Kinesiology* 1 (1): 20–33. doi:10.1016/1050-6411(91)90023-X.

Merton, P. A. 1954. “Voluntary Strength and Fatigue.” *The Journal of Physiology* 123 (3): 553–64. doi:10.1113/jphysiol.1954.sp005070.

Millet, G. P., R. Faiss, and V. Pialoux. 2012. “Point: Counterpoint: Hypobaric Hypoxia Induces/Does Not Induce Different Responses from Normobaric Hypoxia.” *Journal of Applied Physiology* 112: 1783–4. doi:10.1152/japplphysiol.00067.2012.

Millet, G.Y., D. Aubert, F.B. Favier, T. Busso, and H. Benoît. 2009. “Effect of Acute Hypoxia on Central Fatigue During Repeated Isometric Leg Contractions.” *Scandinavian Jour-*

*nal of Medicine & Science in Sports* 19 (5): 695–702. doi:10.1111/j.1600-0838.2008.00823.x.

Millet, Gregoire P., Franck Brocherie, Raphael Faiss, and Olivier Girard. 2015. *Entrainement En Altitude Dans Les Sports Collectifs : Aptitude Aérobie et Répétition de Sprints.* Louvain-La-Neuve (Belgique). De Boeck supérieur.

Millet, Grégoire P, Raphael Faiss, and Vincent Pialoux. 2013. "Evidence for Differences Between Hypobaric and Normobaric Hypoxia Is Conclusive." *Exercise and Sport Sciences Reviews* 41 (2): 133–33. doi:10.1097/JES.0b013e318271a5e1.

Millet, Grégoire P, B Roels, L Schmitt, X Woorons, and J P Richalet. 2010. "Combining Hypoxic Methods for Peak Performance." *Journal of Sports Medicine* 40 (1): 1–25.

Millet, Grégoire P., and Olivier Girard. 2017. "High-Intensity Exercise in Hypoxia-Beneficial Aspects and Potential Drawbacks." *Frontiers in Physiology* 8: 1017.

Millet, Grégoire P., Rob C.I. Wüst, Li Zuo, Thomas Chaillou, Bengt Kayser, François B. Favier, Andrew J. Murray, et al. 2017. "Commentaries on Viewpoint: Human Skeletal Muscle Wasting in Hypoxia: A Matter of Hypoxic Dose?" *Journal of Applied Physiology* 122 (2): 409–11. doi:10.1152/japplphysiol.01084.2016.

Morin, Jean-Benoît, and Pierre Samozino. 2016. "Interpreting Power-Force-Velocity Profiles for Individualized and Specific Training." *International Journal of Sports Physiology and Performance* 11 (2): 267–72. doi:10.1123/ijspp.2015-0638.

Moritani, T., and H. A. deVries. 1979. "Neural Factors Versus Hypertrophy in the Time Course of Muscle Strength Gain." *American Journal of Physical Medicine* 58 (3): 115–30.

Moritani, TOSHIO, MASUO Muro, and AKIRA Nagata. 1986. "Intramuscular and Surface Electromyogram Changes During Muscle Fatigue." *Journal of Applied Physiology* 60 (4): 1179–85.

Murphy, A. J., and G. J. Wilson. 1996. "Poor Correlations Between Isometric Tests and Dynamic Performance: Relationship to Muscle Activation." *European Journal of Applied*

*Physiology and Occupational Physiology* 73 (3-4): 353–57.

Narici, M. V., H. Hoppeler, B. Kayser, L. Landoni, H. Claassen, C. Gavardi, M. Conti, and P. Cerretelli. 1996. "Human Quadriceps Cross-Sectional Area, Torque and Neural Activation During 6 Months Strength Training." *Acta Physiologica Scandinavica* 157 (2): 175–86. doi:10.1046/j.1365-201X.1996.483230000.x.

Narici, M., M. Franchi, and C. Maganaris. 2016. "Muscle Structural Assembly and Functional Consequences." *Journal of Experimental Biology* 219 (2): 276–84. doi:10.1242/jeb.128017.

Narici, Marco V., and Bengt Kayser. 1995. "Hypertrophic Response of Human Skeletal Muscle to Strength Training in Hypoxia and Normoxia." *European Journal of Applied Physiology and Occupational Physiology* 70 (3): 213–19.

Newton, R. U., W. J. Kraemer, and K. Häkkinen. 1999. "Effects of Ballistic Training on Preseason Preparation of Elite Volleyball Players." *Medicine and Science in Sports and Exercise* 31 (2): 323–30.

Newton, Robert U., William J. Kraemer, Keijo Häkkinen, Brendan J. Humphries, and Aron J. Murphy. 1996. "Kinematics, Kinetics, and Muscle Activation During Explosive Upper Body Movements." *Journal of Applied Biomechanics* 12 (1): 31–43.

Nindl, BRADLEY C., CARA D. Leone, WILLIAM J. Tharion, RICHARD F. Johnson, JOHN W. Castellani, JOHN F. Patton, and SCOTT J. Montain. 2002. "Physical Performance Responses During 72 H of Military Operational Stress." *Medicine & Science in Sports & Exercise* 34 (11): 1814–22.

Nishimura, Akinobu, Masaaki Sugita, Ko Kato, Aki Fukuda, Akihiro Sudo, and Atsumasa Uchida. 2010. "Hypoxia Increases Muscle Hypertrophy Induced by Resistance Training." *International Journal of Sports Physiology and Performance* 5 (4): 497–508. doi:10.1123/ijspp.5.4.497.

Noorkoiv, M., K. Nosaka, and A. J. Blazevich. 2010. "Assessment of Quadriceps Muscle

Cross-Sectional Area by Ultrasound Extended-Field-of-View Imaging." *European Journal of Applied Physiology* 109 (4): 631–39. doi:10.1007/s00421-010-1402-1.

Oliver, Jonathan M., Andreas Kreutzer, Shane C. Jenke, Melody D. Phillips, Joel B. Mitchell, and Margaret T. Jones. 2016. "Velocity Drives Greater Power Observed During Back Squat Using Cluster Sets." *Journal of Strength and Conditioning Research* 30 (1): 235–43. doi:10.1519/JSC.0000000000001023.

Orizio, C, F Esposito, and A Veicsteinas. 1994. "Effect of Acclimatization to High Altitude (5,050 M) on Motor Unit Activation Pattern and Muscle Performance." *Journal of Applied Physiology* 77 (6): 2840–4.

Pareja-Blanco, F., D. Rodríguez-Rosell, L. Sánchez-Medina, E. Gorostiaga, and J. J. González-Badillo. 2014. "Effect of Movement Velocity During Resistance Training on Neuromuscular Performance." *International Journal of Sports Medicine* 35 (11): 916–24. doi:10.1055/s-0033-1363985.

Peronnet, F., G. Thibault, and D. L. Cousineau. 1991. "A Theoretical Analysis of the Effect of Altitude on Running Performance." *Journal of Applied Physiology* 70 (1): 399–404. doi:10.1152/jappl.1991.70.1.399.

Perrey, Stéphane, and Thomas Rupp. 2009. "Altitude-Induced Changes in Muscle Contractile Properties." *High Altitude Medicine & Biology* 10 (2): 175–82. doi:10.1089/ham.2008.1093.

Peterson, Kyle. 2017. "Mbir: Magnitude-Based Inferences."

Pérez-Castilla, Alejandro, Belén Feriche, Slobodan Jaric, Paulino Padial, and Amador García-Ramos. 2017. "Validity of a Linear Velocity Transducer for Testing Maximum Vertical Jumps." *Journal of Applied Biomechanics* 33 (5): 388–92. doi:10.1123/jab.2016-0142.

Pérez-Castilla, Alejandro, Amador García-Ramos, P. Padial, Antonio J. Morales-Artacho, and Belén Feriche. 2018. "Effect of Different Velocity Loss Thresholds During a Power-Oriented Resistance Training Program on the Mechanical Capacities of Lower-Body Muscles."

*Journal of Sports Sciences* 36 (12). Routledge: 1331–9.

Pérez-Castilla, Alejandro, Amador García-Ramos, Paulino Padial, Antonio J. Morales-Artacho, and Belén Feriche. 2017. "Load-Velocity Relationship in Variations of the Half-Squat Exercise: Influence of Execution Technique." *Journal of Strength and Conditioning Research*, September. doi:10.1519/JSC.0000000000002072.

Ramos-Campo, Domingo J., Jacobo A. Rubio-Arias, Stéphane Dufour, Linda Chung, Vicente Ávila-Gandía, and Pedro E. Alcaraz. 2017a. "Biochemical Responses and Physical Performance During High-Intensity Resistance Circuit Training in Hypoxia and Normoxia." *European Journal of Applied Physiology* 117 (4): 809–18. doi:10.1007/s00421-017-3571-7.

Ramos-Campo, Domingo J., Jacobo Á. Rubio-Arias, Tomás T. Freitas, Arturo Camacho, José F. Jiménez-Diaz, and Pedro E. Alcaraz. 2017b. "Acute Physiological and Performance Responses to High-Intensity Resistance Circuit Training in Hypoxic and Normoxic Conditions:" *Journal of Strength and Conditioning Research* 31 (4): 1040–7. doi:10.1519/JSC.0000000000001572.

Randell, Aaron D., John B. Cronin, Justin W. L. Keogh, Nicholas D. Gill, and Murray C. Pedersen. 2011. "Effect of Instantaneous Performance Feedback During 6 Weeks of Velocity-Based Resistance Training on Sport-Specific Performance Tests." *Journal of Strength and Conditioning Research* 25 (1): 87–93. doi:10.1519/JSC.0b013e3181fee634.

Revelle, William. 2017. *Psych: Procedures for Psychological, Psychometric, and Personality Research.* Evanston, Illinois: Northwestern University.

Río-Rodríguez, Dan, Eliseo Iglesias-Soler, and Miguel Fernández del Olmo. 2016. "Set Configuration in Resistance Exercise: Muscle Fatigue and Cardiovascular Effects." Edited by Laszlo Csernoch. *PLOS ONE* 11 (3): e0151163. doi:10.1371/journal.pone.0151163.

Roberts, T. J. 2016. "Contribution of Elastic Tissues to the Mechanics and Energetics of Muscle Function During Movement." *Journal of Experimental Biology* 219 (2): 266–75.

doi:10.1242/jeb.124446.

Rodacki, André Luiz Felix, Neil E. Fowler, and Simon J. Bennett. 2002. “Vertical Jump Coordination: Fatigue Effects.” *Medicine and Science in Sports and Exercise* 34 (1): 105–16.

Rooney, K. J., R. D. Herbert, and R. J. Balnave. 1994. “Fatigue Contributes to the Strength Training Stimulus.” *Medicine and Science in Sports and Exercise* 26 (9): 1160–4.

Ruggiero, Luca, Alexandra F. Yacyshyn, Jane Nettleton, and Chris J. McNeil. 2017. “UBC-Nepal Expedition: Acclimatization to High-Altitude Increases Spinal Motoneurone Excitability During Fatigue in Humans.” *The Journal of Physiology*, n/a–n/a. doi:10.1113/JP274872.

———. 2018. “Reply from Luca Ruggiero, Alexandra F. Yacyshyn, Jane Nettleton and Chris J. McNeil: Response to Letter.” *The Journal of Physiology* 596 (15): 3427–7. doi:10.1113/JP275978.

Rupp, Thomas, and Stéphane Perrey. 2009. “Effect of Severe Hypoxia on Prefrontal Cortex and Muscle Oxygenation Responses at Rest and During Exhaustive Exercise.” *Advances in Experimental Medicine and Biology* 645: 329–34. doi:10.1007/978-0-387-85998-9_49.

Ryan, Eric D., Trent J. Herda, Pablo B. Costa, Jason M. Defreitas, Travis W. Beck, Jeffrey R. Stout, and Joel T. Cramer. 2009. “Passive Properties of the Muscle-Tendon Unit: The Influence of Muscle Cross-Sectional Area.” *Muscle & Nerve* 39 (2): 227–29. doi:10.1002/mus.21218.

Rønnestad, B. R., and I. Mujika. 2014. “Optimizing Strength Training for Running and Cycling Endurance Performance: A Review.” *Scandinavian Journal of Medicine & Science in Sports* 24 (4): 603–12. doi:10.1111/sms.12104.

Sahaly, R., H. Vandewalle, T. Driss, and H. Monod. 2001. “Maximal Voluntary Force and Rate of Force Development in Humans - Importance of Instruction.” *European Journal of Applied Physiology* 85 (3-4): 345–50. doi:10.1007/s004210100451.

Sale, D. G. 1988. “Neural Adaptation to Resistance Training.” *Medicine and Science in*

*Sports and Exercise* 20 (5 Suppl): S135–145.

Samozino, Pierre, Enrico Rejc, Pietro Enrico Di Prampero, Alain Belli, and Jean-Benoît Morin. 2012. "Optimal Force-Velocity Profile in Ballistic Movements–Altius: Citius or Fortius?" *Medicine and Science in Sports and Exercise* 44 (2): 313–22. doi:10.1249/MSS.0b013e31822d757a.

Saugy, Jonas J., Laurent Schmitt, Roberto Cejuela, Raphael Faiss, Anna Hauser, Jon P. Wehrlin, Benjamin Rudaz, Audric Delessert, Neil Robinson, and Grégoire P. Millet. 2014. "Comparison of 'Live High-Train Low' in Normobaric Versus Hypobaric Hypoxia." *PLoS ONE* 9 (12): e114418–e114418. doi:10.1371/journal.pone.0114418.

Savourey, Gustave, Jean-Claude Launay, Yves Besnard, Angélique Guinet, and Stéphane Travers. 2003. "Normo- and Hypobaric Hypoxia: Are There Any Physiological Differences?" *European Journal of Applied Physiology* 89 (2): 122–26. doi:10.1007/s00421-002-0789-8.

Sánchez-Medina, Luis, and Juan José González-Badillo. 2011. "Velocity Loss as an Indicator of Neuromuscular Fatigue During Resistance Training." *Medicine and Science in Sports and Exercise* 43 (9): 1725–34. doi:10.1249/MSS.0b013e318213f880.

Schoenfeld, Brad J., Dan I. Ogborn, Andrew D. Vigotsky, Martino V. Franchi, and James W. Krieger. 2017. "Hypertrophic Effects of Concentric Vs. Eccentric Muscle Actions: A Systematic Review and Meta-Analysis." *Journal of Strength and Conditioning Research* 31 (9): 2599–2608. doi:10.1519/JSC.0000000000001983.

Scott, Brendan R., Grant M. Duthie, Heidi R. Thornton, and Ben J. Dascombe. 2016. "Training Monitoring for Resistance Exercise: Theory and Applications." *Sports Medicine* 46 (5): 687–98. doi:10.1007/s40279-015-0454-0.

Scott, Brendan R., Katie M. Slattery, and Ben J. Dascombe. 2014. "Intermittent Hypoxic Resistance Training: Does It Provide Added Benefit?" *Frontiers in Physiology* 5 (October): 397–97. doi:10.3389/fphys.2014.00397.

Scott, Brendan R., Katie M. Slattery, Dean V. Sculley, and Ben J. Dascombe. 2017. "Hypoxia

During Resistance Exercise Does Not Affect Physical Performance, Perceptual Responses, or Neuromuscular Recovery:” *Journal of Strength and Conditioning Research*, December, 1. doi:10.1519/JSC.0000000000002304.

Scott, Brendan R., Katie M. Slattery, Dean V. Sculley, Jacob A. Hodson, and Ben J. Dascombe. 2015. “Physical Performance During High-Intensity Resistance Exercise in Normoxic and Hypoxic Conditions:” *Journal of Strength and Conditioning Research* 29 (3): 807–15. doi:10.1519/JSC.0000000000000680.

Scott, Brendan R., Katie M. Slattery, Dean V. Sculley, Catriona Lockhart, and Ben J. Dascombe. 2017. “Acute Physiological Responses to Moderate-Load Resistance Exercise in Hypoxia.” *The Journal of Strength & Conditioning Research* 31 (7): 1973–81.

Scott, Brendan R., Katie M. Slattery, Dean V. Sculley, Scott M. Smith, Jeremiah J. Peiffer, and Ben J. Dascombe. 2017. “Acute Physiological and Perceptual Responses to High-Load Resistance Exercise in Hypoxia.” *Clinical Physiology and Functional Imaging*, July. doi:10.1111/cpf.12451.

Seals, R, G Johnson, and F Fregosi. 1991. “Hypoxia Potentiates Exercise-Induced Neural Activation in Humans.” *Journal of Applied Physiology* 71 (3): 1032–40.

Secomb, Josh L., Sophia Nimphius, Oliver R.L. Farley, Lina Lundgren, Tai T. Tran, and Jeremy M. Sheppard. 2016. “Lower-Body Muscle Structure and Jump Performance of Stronger and Weaker Surfing Athletes.” *International Journal of Sports Physiology and Performance* 11 (5): 652–57. doi:10.1123/ijspp.2015-0481.

Sejersted, O. M., A. R. Hargens, K. R. Kardel, P. Blom, O. Jensen, and L. Hermansen. 1984. “Intramuscular Fluid Pressure During Isometric Contraction of Human Skeletal Muscle.” *Journal of Applied Physiology: Respiratory, Environmental and Exercise Physiology* 56 (2): 287–95. doi:10.1152/jappl.1984.56.2.287.

Semmler, J.G., and R. M. Enoka. 2000. “Neural Contributions to Changes in Muscle Strength.” In *Biomechanics in Sport*, edited by Vladimir M. Zatsiorsky, 2–20. Oxford, UK: Blackwell Science Ltd. doi:10.1002/9780470693797.ch1.

Street, Glenn, Scott McMillan, Wayne Board, Mike Rasmussen, and J. Michael Heneghan. 2001. "Sources of Error in Determining Countermovement Jump Height with the Impulse Method." *Journal of Applied Biomechanics* 17 (1): 43–54. doi:10.1123/jab.17.1.43.

Strojnik, V., and P. V. Komi. 1998. "Neuromuscular Fatigue After Maximal Stretch-Shortening Cycle Exercise." *Journal of Applied Physiology (Bethesda, Md.: 1985)* 84 (1): 344–50.

Stulen, Foster B., and Carlo J. De Luca. 1978. "The Relation Between the Myoelectric Signal and Physiological Properties of Constant-Force Isometric Contractions." *Electroencephalography and Clinical Neurophysiology* 45 (6): 681–98. doi:10.1016/0013-4694(78)90137-2.

Suchomel, Timothy J., Sophia Nimphius, and Michael H. Stone. 2016. "The Importance of Muscular Strength in Athletic Performance." *Sports Medicine* 46 (10): 1419–49. doi:10.1007/s40279-016-0486-0.

Sugiura, Yoshito, Yasuhiko Hatanaka, Tomoaki Arai, Hiroaki Sakurai, and Yoshikiyo Kanada. 2016. "Estimations of One Repetition Maximum and Isometric Peak Torque in Knee Extension Based on the Relationship Between Force and Velocity:" *Journal of Strength and Conditioning Research* 30 (4): 980–88. doi:10.1519/JSC.0000000000001187.

Sweet, Travis W., Carl Foster, Michael R. McGuigan, and Glenn Brice. 2004. "Quantitation of Resistance Training Using the Session Rating of Perceived Exertion Method." *Journal of Strength and Conditioning Research* 18 (4): 796–802. doi:10.1519/14153.1.

Szubski, Christoph, Martin Burtscher, and Wolfgang N Löscher. 2006. "The Effects of Short-Term Hypoxia on Motor Cortex Excitability and Neuromuscular Activation." *Journal of Applied Physiology (Bethesda, Md. : 1985)* 101 (6): 1673–7. doi:10.1152/japplphysiol.00617.2006.

———. 2007. "Neuromuscular Fatigue During Sustained Contractions Performed in Short-Term Hypoxia." *Medicine and Science in Sports and Exercise* 39 (6): 948–54.

doi:10.1249/mss.0b013e3180479918.

Thomas, Christopher, Paul Comfort, Paul A. Jones, and Thomas Dos'Santos. 2016. "A Comparison of Isometric Mid-Thigh Pull Strength, Vertical Jump, Sprint Speed, and Change of Direction Speed in Academy Netball Players." *International Journal of Sports Physiology and Performance*, December, 1–20. doi:10.1123/ijspp.2016-0317.

Thomas, Christopher, Paul A. Jones, James Rothwell, Chieh Y. Chiang, and Paul Comfort. 2015. "An Investigation into the Relationship Between Maximum Isometric Strength and Vertical Jump Performance." *The Journal of Strength & Conditioning Research* 29 (8): 2176–85.

Thomas, Kevin, Stuart Goodall, and Glyn Howatson. 2018. "Performance Fatigability Is Not Regulated to A Peripheral Critical Threshold:" *Exercise and Sport Sciences Reviews* 46 (4): 240–46. doi:10.1249/JES.0000000000000162.

Thompson, Christopher K., Francesco Negro, Michael D. Johnson, Matthew R. Holmes, Laura Miller McPherson, Randall K. Powers, Dario Farina, and Charles J. Heckman. 2018. "Robust and Accurate Decoding of Motoneuron Behaviour and Prediction of the Resulting Force Output." *The Journal of Physiology* 596 (14): 2643–59. doi:10.1113/JP276153.

Tillin, N. A., M. T. G. Pain, and J. P. Folland. 2012. "Contraction Type Influences the Human Ability to Use the Available Torque Capacity of Skeletal Muscle During Explosive Efforts." *Proceedings of the Royal Society B: Biological Sciences* 279 (1736): 2106–15. doi:10.1098/rspb.2011.2109.

Tillin, N. A., M. Pain, and J. P. Folland. 2013a. "Explosive Force Production During Isometric Squats Correlates with Athletic Performance in Rugby Union Players." *Journal of Sports Sciences* 31 (1): 66–76. doi:10.1080/02640414.2012.720704.

Tillin, N. A., Matthew T. G. Pain, and J. P. Folland. 2013b. "Identification of Contraction Onset During Explosive Contractions. Response to Thompson et Al. 'Consistency of Rapid Muscle Force Characteristics: Influence of Muscle Contraction Onset Detection Methodology'

[J Electromyogr Kinesiol 2012;22(6):893-900].” *Journal of Electromyography and Kinesiology: Official Journal of the International Society of Electrophysiological Kinesiology* 23 (4): 991–94. doi:10.1016/j.jelekin.2013.04.015.

Tillin, N. A., Matthew T. G. Pain, and Jonathan P. Folland. 2018. “Contraction Speed and Type Influences Rapid Utilisation of Available Muscle Force: Neural and Contractile Mechanisms.” *The Journal of Experimental Biology*, October, jeb.193367. doi:10.1242/jeb.193367.

Trezise, J., N. Collier, and A. J. Blazevich. 2016. “Anatomical and Neuromuscular Variables Strongly Predict Maximum Knee Extension Torque in Healthy Men.” *European Journal of Applied Physiology* 116 (6): 1159–77. doi:10.1007/s00421-016-3352-8.

Tufano, James J., Jenny A. Conlon, Sophia Nimphius, Lee E. Brown, Harry G. Banyard, Bryce D. Williamson, Leslie G. Bishop, Amanda J. Hopper, and G. Gregory Haff. 2017. “Cluster Sets: Permitting Greater Mechanical Stress Without Decreasing Relative Velocity.” *International Journal of Sports Physiology and Performance* 12 (4): 463–69. doi:10.1123/ijspp.2015-0738.

Tufano, James J., Jenny A. Conlon, Sophia Nimphius, Lee E. Brown, Laurent B. Seitz, Bryce D. Williamson, and G. Gregory Haff. 2016. “Maintenance of Velocity and Power with Cluster Sets During High-Volume Back Squats.” *International Journal of Sports Physiology and Performance* 11 (7): 885–92. doi:10.1123/ijspp.2015-0602.

Van Cutsem, M., J. Duchateau, and K. Hainaut. 1998. “Changes in Single Motor Unit Behaviour Contribute to the Increase in Contraction Speed After Dynamic Training in Humans.” *The Journal of Physiology* 513 ( Pt 1) (November): 295–305.

Van Cutsem, Michaël, and Jacques Duchateau. 2005. “Preceding Muscle Activity Influences Motor Unit Discharge and Rate of Torque Development During Ballistic Contractions in Humans: Motor Unit Discharge Pattern During Ballistic Contractions.” *The Journal of Physiology* 562 (2): 635–44. doi:10.1113/jphysiol.2004.074567.

Vandewalle, H., G. Peres, J. Heller, J. Panel, and H. Monod. 1987. “Force-Velocity Relationship and Maximal Power on a Cycle Ergometer: Correlation with the Height of a Vertical Jump." *European Journal of Applied Physiology and Occupational Physiology* 56 (6): 650–56. doi:10.1007/BF00424805.

Voigt, M., F. Chelli, and C. Frigo. 1998. "Changes in the Excitability of Soleus Muscle Short Latency Stretch Reflexes During Human Hopping After 4 Weeks of Hopping Training." *European Journal of Applied Physiology and Occupational Physiology* 78 (6): 522–32. doi:10.1007/s004210050455.

Vøllestad, Nina K. 1997. "Measurement of Human Muscle Fatigue." *Journal of Neuroscience Methods* 74 (2): 219–27.

Walker, Simon, Lisa Davis, Janne Avela, and Keijo Häkkinen. 2012. "Neuromuscular Fatigue During Dynamic Maximal Strength and Hypertrophic Resistance Loadings." *Journal of Electromyography and Kinesiology* 22 (3): 356–62. doi:10.1016/j.jelekin.2011.12.009.

Walker, Simon, Heikki Peltonen, Janne Avela, and Keijo Häkkinen. 2013. "Neuromuscular Fatigue in Young and Older Men Using Constant or Variable Resistance." *European Journal of Applied Physiology* 113 (4): 1069–79. doi:10.1007/s00421-012-2526-2.

Wehrlin, Jon Peter, and Jostein Hallén. 2006. "Linear Decrease in .VO2max and Performance with Increasing Altitude in Endurance Athletes." *European Journal of Applied Physiology* 96 (4): 404–12. doi:10.1007/s00421-005-0081-9.

Wei, Taiyun, and Viliam Simko. 2017. *R Package 'Corrplot': Visualization of a Correlation Matrix*.

Wickiewicz, THOMAS L., ROLAND R. Roy, PERRY L. Powell, JAMES J. Perrine, and V. REGGIE Edgerton. 1984. "Muscle Architecture and Force-Velocity Relationships in Humans." *Journal of Applied Physiology* 57 (2): 435–43.

Wilhelm, Eurico N., Regis Radaelli, Da Silva, Bruna G.c, Cíntia E. Botton, Rafael Barbosa, Martim Bottaro, Lee E. Brown, and Ronei S. Pinto. 2013. "Single-Joint Isometric Rate of Torque Development Is Not Related to Counter- Movement Jump Performance in Soccer

Players." *Isokinetics and Exercise Science* 21 (3): 181–86. doi:10.3233/IES-130513.

Willer, J. C., G. Miserocchi, and H. Gautier. 1987. "Hypoxia and Monosynaptic Reflexes in Humans." *Journal of Applied Physiology (Bethesda, Md.: 1985)* 63 (2): 639–45. doi:10.1152/jappl.1987.63.2.639.

Winter, Edward M., Grant Abt, FB Carl Brookes, John H. Challis, Neil E. Fowler, Duane V. Knudson, Howard G. Knuttgen, et al. 2016. "Misuse of 'Power' and Other Mechanical Terms in Sport and Exercise Science Research." *The Journal of Strength & Conditioning Research* 30 (1): 292–300.

Yan, Bing, Xiangxun Lai, Longyan Yi, Yang Wang, and Yang Hu. 2016. "Effects of Five-Week Resistance Training in Hypoxia on Hormones and Muscle Strength." *The Journal of Strength & Conditioning Research* 30 (1): 184–93.

Young, A, J Wright, J Knapik, and A Cymerman. 1980. "Skeletal Muscle Strength During Exposure to Hypobaric Hypoxia." *Medicine and Science in Sports and Exercise* 12 (5): 330–35.

Yue, G., and K. J. Cole. 1992. "Strength Increases from the Motor Program: Comparison of Training with Maximal Voluntary and Imagined Muscle Contractions." *Journal of Neurophysiology* 67 (5): 1114–23. doi:10.1152/jn.1992.67.5.1114.

Zamparo, P., A. E. Minetti, and P. E. di Prampero. 2002. "Interplay Among the Changes of Muscle Strength, Cross-Sectional Area and Maximal Explosive Power: Theory and Facts." *European Journal of Applied Physiology* 88 (3): 193–202. doi:10.1007/s00421-002-0691-4.

Zehr, E. Paul, and Digby G. Sale. 1994. "Ballistic Movement: Muscle Activation and Neuromuscular Adaptation." *Canadian Journal of Applied Physiology* 19 (4): 363–78.

Zhou, Shi. 2000. "Chronic Neural Adaptations to Unilateral Exercise: Mechanisms of Cross Education." *Exercise and Sport Sciences Reviews* 28 (4): 177.