The effects of high resistance training volume during caloric restriction among resistance-trained individuals on body composition, resting energy expenditure, 24-hour total nitrogen balance and maximal strength

Samir Nait-Yahia

Thesis submitted to the University of Ottawa

in partial fulfillment of the requirements for the

degree of Master of Science in Human Kinetics

School of Human Kinetics

Faculty of health sciences

University of Ottawa

Abstract

Background

Athletes employ weight-loss protocols to lower fat mass (FM) and maintain fat-free mass (FFM) for performance purposes. Under mass-stable conditions, high resistance training volumes (HVRT) have been associated with greater increases in FFM than low resistance training volumes (LVRT). However, less is known about the effects of HVRT under caloric restriction (CR). Therefore, it remains unclear whether HVRT could elicit greater retention of FFM and improvements in strength during CR.

Objectives

Determine the effects of HVRT and high protein intake on FFM and strength in resistance-trained individuals after a 40% CR.

Methods

Sixteen resistance-trained individuals underwent a high-protein (2.3g/kg body mass [BM]), 4-week 40% CR with a 5-day/week resistance training intervention. Participants were randomly assigned to LVRT (12 sets/muscle group/week) or HVRT (30 sets/muscle group/week). Pre- and post intervention testing included dual energy X-ray absorptiometry, indirect calorimetry, dietary records, resistance training records, 5 RM strength testing and nitrogen balance.

Results

Significant reductions in BM ($\Delta - 4.20$kg $\pm$ 0.50, $p < 0.001$), FM ($\Delta - 3.66$kg $\pm$ 0.42kg, $p < 0.001$) and %FM ($\Delta - 3.49\% \pm 0.43\%$, $p < 0.001$) were observed, but changes were not different between groups. No intervention or group by intervention effects were noted for FFM. HVRT had greater increases for 5 RM testing for chest press ($p = 0.058$), right leg press ($p = 0.03$) and left leg press ($p = 0.02$).

Conclusion

HVRT does not seem to further enhance FFM retention during a 40% CR. Greater increases in strength were noted in HVRT, but mechanisms underlying such improvements remain to be investigated.

Table of contents

List of Abbreviations

Abbreviation	Definition
BM	Body Mass
CR	Caloric Restriction
DXA	Dual Energy X-Ray Absorptiometry
EB	Energy Balance
EI	Energy Intake
FFM	Fat-Free Mass
FM	Fat Mass
HVRT	High-Volume Resistance Training
ILWO	Individual Living with Overweight
LVRT	Low-Volume Resistance Training
MPB	Muscle Protein Breakdown
MPS	Muscle Protein Synthesis
NBAL	Nitrogen Balance
NREE	Non-Resting Energy Expenditure
REE	Resting Energy Expenditure
RM	Repetition Maximum
RT	Resistance Training
RTV	Resistance Training Volume
TDEE	Total Daily Energy Expenditure
TEF	Thermic Effect of Food
TUT	Time Under Tension
VL	Volume Load

Chapter 1: Introduction

Caloric restriction (CR) combined with resistance training (RT) is a common strategy used among athletes to reduce fat mass (FM) while preserving fat-free mass (FFM) (Longland *et al*., 2016 ; Mettler *et al*., 2010 ; Ferguson *et al*., 2009). This approach is often used by athletes aiming to enhance their power-to-mass ratio, which can improve sport-related performances (Ferguson *et al*., 2009 ; Pons *et al*., 2018). However, CR has previously been reported to induce FFM losses (Heymsfield *et al*., 2024 ; Weinheimer *et al*., 2010). Given that higher levels of FFM have been associated with greater strength/power output (NCSA, 2021), reducing the extent of FFM losses is of primary importance for athletes.

Notable strategies used by athletes to reduce such losses during CR include macronutrient intake alterations (e.g., increased protein intake) and RT practice (Longland *et al*., 2016 ; Hector *et* Phillips, 2018). Extensive research has been conducted on the influence of protein intake on FFM sparing, and it is well documented that lean athletes undergoing CR may benefit from increased protein intake (Helms *et al*., 2014 ; Hector *et* Phillips, 2018). However, nutritional intervention alone may not provide a strong enough stimulus to preserve FFM, as 25% of the body mass (BM) lost is attributable to FFM, while incorporating RT mitigate these losses to about 11% (Weinheimer *et al*., 2010). Additionally, despite clear guidelines as to how RT should be performed to maximize hypertrophy under mass-stable conditions, *how* athletes and resistance-trained individuals should modify their RT parameters to maximize FFM retention while undergoing CR remains largely unanswered.

It is well accepted that high-volume resistance training (HVRT) alongside sufficient protein intake provides strong stimuli for hypertrophy. In fact, many suggested that HVRT was the main driver of hypertrophy (Schoenfeld *et al*., 2017), which would suggest that the incorporation of HVRT during CR may provide additional benefits for FFM sparing. Meta-analyses conducted under mass-stable conditions by Schoenfeld *et al*. (2017) and Remmert *et al*. (2025) both reported a reversed U-shaped relationship between hypertrophy and resistance training volume (RTV), yet both groups failed to identify a clear plateau between RTV and hypertrophy. Furthermore, both groups mainly included studies conducted among untrained individuals, who may respond differently to RT than trained individuals. Finally, lack of studies using RTV > 20 sets/muscle group/week leaves a gap regarding the use of such RTV on hypertrophy under energy balance (EB). In contrast, Brigatto *et al*. (2022) showed that 32 sets/muscle group/week yielded greater increases in vastus lateralis muscle thickness than 24 sets/muscle group/week and 16 sets/muscle group/week. Despite failing to reach statistical significance, Schoenfeld *et al*. (2018) showed a graded increase in hypertrophy between 9 sets/muscle group/week, 27 sets/muscle group/week and 45 sets/muscle group/week, suggesting a potential benefit from RTV > 30 sets/muscle group/week. To this day, no study conducted under CR has used such RTV. In fact, the only randomized controlled trial controlling for RTV and conducted under CR did not detect a difference in FFM changes between 12 sets/muscle group/week and 20 sets/muscle group/week (Schoenfeld *et al*., 2023). Of note, reported changes in FFM were within the margin of error of the bioelectrical impedance, which prevented the authors from drawing any clear conclusion regarding the use of such RTV for FFM sparing under CR.

Taken together, current bodies of evidence suggest a potential benefit of HVRT on hypertrophy. However, its applicability to CR remains largely unanswered, mainly due to the limited evidence available. In fact, the only randomized controlled trial conducted on the topic demonstrated that 12 sets/muscle group/week and 20 sets/muscle group/week were equivalent in the sparing of FFM. However, this study has multiple limitations to its applicability: 1) Both groups maintained their RTV when compared to their previous RTV, 2) The 33% deficit was not achieved and 3) The reported changes in FFM were within the margin of error of the bioimpedance (Siedler *et al*., 2021). What is more, only a few studies included direct measurement of hypertrophy (such as muscle thickness), while those reporting body composition changes lacked the incorporation of gold-standard measurements (like the dual-energy X-ray scan [DXA]) or did not combine multiple methods (DXA scan plus 24-hour nitrogen balance [NBAL]) in order to provide an estimate of the quality of FFM changes. For those reasons, it remains to be determined whether > 20 sets/muscle group/week could reduce FFM losses under CR.

Chapter 2: Literature Review

History of Resistance Training

The interest towards aesthetics and performance has been ongoing since the ancient Greek and Egyptian civilizations, way before the appearance of bodybuilding competitions and strength/power disciplines practised today. For example, Greeks perceived broad shoulders and muscular symmetry as signs of healthiness and masculinity (Stojiljković *et al*., 2013). Despite their recognition of the benefits of RT on musculature and health, RT practice was, before 1890, mostly supported by anecdotal evidence coming from practitioners themselves, such as professional strongmen or gym owners (Roberts *et al*., 2023). Between 1894 and 1935, a few practitioner-based books and magazines on the methods of RT were written but lacked empirical evidence from scientific literature (Kraemer *et al*., 2017). In fact, before 1940, little to no research was oriented towards RT for multiple reasons; 1) RT was seen as a form of charlatanism by scientists, where strongmen used trickery instead of their true muscle strength, 2) Overdevelopment of the musculature was thought to induce an underdevelopment of the rest of the body and 3) The law of conservation of energy was still misapplied (Kraemer *et* al., 2017 ; Stojiljković *et al*., 2013). Nonetheless, Dr. Thomas L. Delorme conducted, between 1945 and 1952, the first RT studies aiming to develop RT protocols. Even if his purpose was to create a rehabilitation program for wounded soldiers, his efforts led to the creation of one RT parameter, the intensity, still used today as the percentage of 1 RM (1 repetition maximum) as well as one RT principle, the principle of *progressive overloading* (DeLorme, 1945; Kraemer *et al*., 2017). Additionally, he concluded that lifting heavy loads with fewer repetitions would lead to greater strength increases than low-load high-repetition protocols (DeLorme, 1945). A few years later, the progressive overloading principle was confirmed by Kunisitz *et* Keeney (1958), who showed that progressing from 1 set/exercise to 3 sets/exercise over an 8-week period led to significant increases in strength and muscle girth in college men compared to regular physical activity classes. From 1960 to 1970, RT gained recognition, both in athletic and clinical settings, thanks to the works of Dr. Richard Berger, a former football athlete, weightlifter and professor (Todd *et* Todd, 2013). His most well-known work, *Effect of varied weight training programs on strength*, was the first RT study to use an appropriate statistical analysis for the study design employed (Berger, 1962; Todd *et* Todd, 2013). Using a sample size of n = 177 and RT programs of 1, 2 or 3 sets of 2, 6 or 10 repetitions, he showed that 3 sets or 6 repetitions were the most effective at increasing strength following a 12-week period (Berger, 1962). Importantly, Bergers' works also helped the recognition of RT as a tool to improve sports-related performances. For example, his 1973 study *Effects of strength improvement on accuracy in a gross motor task* showed that performing a 10-week RT routine for the muscles involved during a basket significantly improved 15-foot accuracy compared to a control group of students (Berger, 1973). Research on RTV also saw a rise from 1970 to 2000, with researchers such as William J. Kraemer providing insights on the influence of RT on performances (Berger, 1962 ; Pearson *et al*., 2000), hormonal responses (Volek *et al*., 1997), metabolic health (Volek *et al*., 2000), strength (Mazzetti *et al*., 2000), hypertrophy (Kraemer *et* Pennsylvania State University, 2000), bone mineral density (Humphries *et al*., 2000) as well as on the periodization of RT variables (Kraemer *et al*., 2000). However, as more studies were coming out during that time, controversies about RTV and hypertrophy started rising. For example, many found no difference in hypertrophy between low-volume resistance training (LVRT) and HVRT (Ostrowski *et al*., 1997 ; Starkey *et al*., 1996). The 21st century could be characterized as an era where myths surrounding RT practice are being debunked. For example, high loads were thought to recruit all high-threshold motor units (thus optimizing hypertrophy) while low loads were thought unable to do so. This has been revealed to be untrue (Baechle *et* Earle, 2008). Those findings were later supported as high-load and low-load RT induced similar hypertrophy (Ogasawara *et al*., 2013). The 21st century also saw an increase in the prevalence of meta-analyses and reviews seeking differences in RTV-related hypertrophy changes. For example, Wernbom *et al*. (2007) were among the first to find an effect favouring HVRT for hypertrophy. Ten years later, their findings were supported by Schoenfeld *et al*. (2017), who showed that > 10 sets/muscle group/week provided greater hypertrophic outcomes than < 5 sets/muscle group/week and 5-9 sets/muscle group/week. However, as more research came out, the establishment of a clear dose-response relationship between RTV and hypertrophy became harder, with the most recent meta-analysis failing to identify diminishing returns for RTV-related hypertrophy and despite observing diminishing returns at around 8.2 sets/muscle group/session (Remmert *et al*, 2025). Indeed, differences among studied populations (untrained versus trained, women versus men), instruments used (bioelectrical impedance versus dual-energy X-ray absorptiometry [DXA]) and study designs (sets/muscle groups/week performed, duration of the protocol, multi-joints versus single-joint exercises) make it hard to draw clear guidelines on RTV and hypertrophy. What is more, studies conducted under CR are still lacking, with, to our knowledge, only two papers written on the topic to this day. RT is known to reduce FFM losses during CR, yet *how* RT should be programmed under CR remain largely undefined and underexplored. Therefore, the subsequent sections will put in evidence the acquired knowledge on RTV and hypertrophy and its potential contribution to FFM maintenance under CR.

Skeletal Muscle Hypertrophy

Hypertrophy is described as an increase in mass and/or size. More specifically, the latter can be seen as an increase in the axial cross-sectional area of a pre-existing muscle fibre or muscle by increasing muscle protein (actin and myosin) content (in series or parallel) (Schoenfeld *et al.*, 2020). To our current knowledge, hypertrophy is not induced by an increase in muscle fibres number (hyperplasia), at least in humans (Schoenfeld, 2020). The simplicity of this definition can lead to a misinterpretation of what clearly defines increases (or decreases) of FFM. In fact, FFM changes can occur at different structural levels of organization, including 1) The whole muscle, covered by the epimysium, 2) Muscle fibre bundles within the perimysium and individual muscle fibres within their endomysium, 3) Myofibrils in a given muscle fibre, 4) Sarcomeres in a given myofibril and 5) Actin, myosin and titin content inside a sarcomere (Haun *et al.* 2019). What is more, the use of different measurement techniques can also lead to a misinterpretation of the quality of hypertrophy changes. For example, DXA scan is considered the gold standard for FFM changes but does not differentiate between muscle protein content, organ mass and total body water changes (Bilsborough *et al.*, 2014 ; Haun *et al.*, 2019). Finally, FFM changes may respond differently upon the modification of certain training parameters (intensity and volume, to name a few), of training modality or of training method used by one (eccentric muscle contractions) (Greiwe *et al.*, 1999; Haun *et al.*, 2019; Schoenfeld *et al.*, 2017). The following sections will aim to clarify the current knowledge on hypertrophy and the role of RT parameters on hypertrophy.

Understanding Changes in Muscle Size and Volume

To begin with, hypertrophy is an adaptation of a given muscle following the presence of mechanical constraints (Schoenfeld, 2010). Briefly, the contractions and stretches induced by the mechanical constraints activate mechanoreceptors on the cell membrane, leading to many myogenic events and consequently hypertrophy in presence of adequate protein intake (Atherton *et* Smith, 2012 ; Schiaffino *et al*., 2021 ; Schoenfeld, 2010). All forms of loading can achieve hypertrophy, but RT remains its most potent form of stimulation (Atherton *et* Smith, 2012 ; Ggric *et* al., 2019). Nonetheless, there is still a debate regarding the appropriate definition of hypertrophy. Indeed, FFM changes are not always similar as changes in muscle glycogen content, intracellular fluids, muscle cross-sectional area, fibre cross-sectional area, muscle thickness, sarcoplasmic volume and muscle protein content can all happen following the presence of an external force on muscles (Haun *et al*., 2019). It is important to acknowledge that muscles are mainly composed of water (75% of whole muscle content) and of intracellular proteins, extracellular proteins, muscle glycogen and muscle triglycerides (Haun *et al*., 2019; Marieb *et* Hoehn, 2007). For example, changes in muscle fluids might increase (or decrease) muscle size and volume without increasing muscle protein content. It is accepted that about 3 grams of water can bind to a gram of glucose to form a molecule of glycogen in muscles (Marieb *et* Hoehn, 2007). With respect to the benefits of increasing ones' carbohydrates intake on performance (increased muscle glycogen content leading to greater energy reservoir during exercise bouts), increases in muscle glycogen content are not directly related to muscle protein changes. For example, bodybuilders may undergo periods of carbohydrate loading (increasing carbohydrate intake in a 24- to 48-hour window) following exhaustive exercise to enhance muscle glycogen stores, leading to an increase in muscle thickness and size that may be seen as advantageous while posing on stage (de Moraes *et al.*, 2019). In addition, exercise can also increase muscle glycogen content through increases in GLUT-

4 content (a glucose transporter) (Greiwe *et al.*, 1999). Similarly, some RT protocols and muscle damage are thought to induce changes in intracellular water content. For example, eccentric contractions have been associated with greater muscle damage and inflammatory response (oedema) than concentric contractions, notably by inducing greater disruption to contractile, supportive, and structural elements (Schoenfeld *et al.* 2017). Those fluid changes may be misinterpreted as muscle protein changes when using techniques such as ultrasound imaging or magnetic resonance imaging (Haun *et al*., 2019).

Given that hypertrophy englobes a large panel of structural changes and that most studies report general hypertrophic change, it will be considered either an increase in muscle thickness and/or FFM in this literature review.

Molecular Mechanisms Modulating Skeletal Muscle Mass

FFM is a plastic tissue that adapts to various stimuli, including CR, protein intake and RT (Atherton *et* Smith, 2012). FFM regulation depends on two distinct pathways: muscle protein synthesis (MPS) and muscle protein breakdown (MPB) (Atherton *et* Smith, 2012). MPS and MPB are, by nature, anabolic and catabolic processes, respectively (Atherton *et* Smith, 2012). In adults, MPS is enhanced by the ingestion of amino acids–especially essential amino acids such as leucine–and by the repeated and progressive application of external load on muscle (Atherton *et* Smith, 2012; Schoenfeld, 2010). While both aerobic exercise and RT increase MPS and induce hypertrophy (Grgic *et al*., 2019), aerobic exercise primary promotes mitochondrial biogenesis (mitochondrial protein synthesis) while RT leads to myofibrillar protein synthesis (Atherton *et* Smith, 2012; Ggric *et al*., 2019; Marieb *et* Hoehn, 2007). MPB, on the other hand, is triggered by fasting, CR and prolonged periods of inactivity (Atherton *et* Smith, 2012). The *Mammalian Target of Rapamycin Complex-1* is considered the central regulator of these processes: its activation stimulates downstream effectors (p70S6K, EIF4EBP1, ULK1), thereby promoting ribosomal protein synthesis and suppressing autophagy, whereas inhibition enhances proteolysis (Drummond *et al*., 2009; Goodman *et al*., 2011; Atherton *et* Smith, 2012; Hasegawa *et al*., 2022). Under CR, MPS is down-regulated, likely to reduce nonessential energetic costs (Atherton *et* Smith, 2012 ; Elia *et al*., 1999). Consequently, reliance on endogenous substrate–FFM, FM, and glycogen–increases to meet metabolic demands (Elia *et al*., 1999). On the other hand, MPB remains stable or increases, resulting in a net loss of amino acids, as reported among normal weight and healthy young men showing a negative state of NBAL following a 3-week 40% CR (Friedlander *et al*., 2005). Even though measuring NBAL reflects whole-body protein turnover, it would be more than detrimental to degrade proteins coming from essential organs such as the liver or the kidneys. Knowing that inducing hypertrophy is non-necessary for proper functioning of the human body, it seems plausible to assume that NBAL mostly reflects, at least under relatively short CR, a state of muscle protein changes (Konstantinide, 1992). Interestingly, a randomized-controlled trial conducted over a 3-week period showed that, during a 30% CR, increasing protein intake from 0.8g/kg to about 1.6g/kg or 2.4g/kg led to a graded increase in protein oxidation in the fasted state (95.4 ± 2.8 mmol/kg/h and 98.9 ± 3.0 mmol/kg/h, respectively) (Pasiakos *et al*., 2014). Of consideration, the graded increase in protein oxidation was also present under their pre-CR EB week, which suggests that increases in protein oxidation can occur both from increasing protein intake and increased reliance on body protein. To our knowledge, there is no study specifically seeking differences between RTV on MPS and MPB changes during CR. In resistance-trained men under EB, 3 sets of unilateral leg extension led to greater myofibrillar protein synthesis than 1 set 5 hours following their RT bout ($p = 0.008$) (Burd *et al*., 2010). Furthermore, 29 hours after their RT bout, MPS rates remained significantly elevated above rest values only for the 3-set group. Under CR, 6 sets of 8 repetitions showed values for *Mammalian Target of Rapamycin*

Complex-1 and p70S6K phosphorylation higher than those observed for the control condition, which was under EB and at rest (Areta *et al*., 2014). These values were also higher than those found by Pasiakos *et al.* (2013), who used a similar CR, but lower intensity and RTV intervention.

Unfortunately, methodological differences and lack of studies comparing different RTV under CR makes it difficult to establish a clear relationship between RTV and their influence on the molecular pathways modulating hypertrophy. According to the available data, it remains possible that HVRT might enhance the molecular response modulating hypertrophy to a greater extent. Further studies are necessary to investigate this hypothesis.

Resistance Training Variables and Skeletal Muscle Hypertrophy

Resistance training is the most potent intervention to induce hypertrophy (NCSA, 2021). Additionally, a regular practice of RT has been shown to promote better metabolic health (increased insulin sensitivity, reduction of blood triglycerides and blood low-density lipoprotein), to diminish risks of injury and, to some extent, maintain FFM during periods of CR (NCSA, 2021 ; Roth *et* al., 2022 ; Schoenfeld, 2020). The subsequent sections will aim to clarify the role of RT variables in muscle growth.

Resistance training volume. RTV is thought to be the primary driver of hypertrophy. The methods used to determine ones' RTV include the volume load (tonnage i.e., volume load [VL]), the workload (force [Newton] x displacement [metre]), the maximum volume dynamic strength (sets x repetitions x [body-shank mass + external load]), the time under tension (TUT) (time to perform the concentric and eccentric phases of every single repetition), the number of sets/muscle group/week or simply the number of sets/exercise (NCSA, 2021 ; McBride *et al.,* 2009 ; Schoenfeld, 2020). All those methods have been validated as tools to quantify RTV, but it remains important to acknowledge the limitations of each method when administrating, tracking, and understanding the prescribed RTV. For example, the VL cannot be used for bodyweight exercises (Baz-Valle *et al*., 2021; McBride *et al*., 2009). VL can also lead to a misinterpretation of the “true” work performed during an exercise. For example, a barbell back squat is more demanding (more muscle masses involved) than a standard leg press, yet higher loads are used on the leg press for the same relative intensity (Baz-Valle *et al*., 2021). Concerning the workload, even if accurate by nature as it accounts for the displacement of the centre of mass and for the force exerted, it presents some limitations; 1) It requires at least two people to measure the displacement performed and 2) It requires the use of specialized equipment, which might not be available to everyone (Martson *et* al., 2017 ; McBride *et al.*, 2009). On the other hand, the TUT is a reliable way to measure one’s RTV, but 1) TUT does not account for the load used during an exercise, 2) TUT is easily influenced by the accumulation of fatigue throughout an RT session, making repetitions longer or shorter and leading to a potential overestimation or underestimation of one’s RTV and 3) TUT might differ between exercises during a given session and may not represent the absolute fatigue caused by that exercise (Krzysztofik *et al*., 2019 ; Martson *et al*., 2017 ; McBride *et al*., 2009). Finally, the maximum volume dynamic strength has similar limitations to the VL, but can also induce errors based on: 1) The subjective assessment of one’s capacity to perform maximal efforts over the course of multiple sets and repetitions (increased levels of fatigue and decreased motivation throughout a training) and 2) Maximum volume dynamic strength focuses on the percentage of 1 RM, neglecting the variability among different repetition schemes and intensities (McBride *et al*., 2009). However, a novel and easier method of determining RTV, the number of sets/muscle group/week, has recently been validated, if, according to a recent meta-analysis, the repetition scheme ranges between 6 and 20 repetitions (Baz-Valle *et al.*, 2021). This recommendation might be explained by an insufficient TUT provided by lower repetition schemes and by a certain degree of complexity to attain concentric muscular failure with higher repetition schemes (increased levels of discomfort with higher repetition ranges). The subsequent section will focus on studies conducted under mass-stable condition and will consider RTV described and prescribed in VL and sets/muscle group/week.

According to the American College of Sports Medicine, untrained individuals should perform between 1 and 3 sets/exercise with intensities ranging from 60% to 75% of their 1 RM (Schoenfeld *et* Grgic, 2018). Advanced individuals should, on the other hand, perform somewhere between 4 and 6 sets/exercise at intensities ranging from 70% to 100% of their respective 1 RM (Schoenfeld *et* Grgic, 2018). This difference could be explained by two factors: 1) Hypertrophy is virtually non-existent in untrained individuals, which means that LVRT is more likely to induce similar hypertrophy than HVRT and 2) Chronically trained individuals need to progressively increase their VL and/or modify their RT parameters to progress (NCSA, 2021 ; Schoenfeld, 2020). Furthermore, performing HVRT in untrained individuals might lead to discouragement and high levels of fatigue (NCSA, 2021). For example, Starkey *et al.* (1996) showed that 1 set/exercise (or 3 sets/muscle group/week) and 3 sets/exercise (or 9 sets/muscle group/week) led to similar increases in vastus medialis and vastus lateralis muscle thickness in untrained men and women. In chronically trained individuals, the debate is still ongoing. In resistance-trained men, 3 sets of unilateral leg extensions led to greater increases in myofibrillar protein synthesis and intracellular signalling proteins phosphorylation (EIF4EBP1, ribosomal protein S6) than 1 set, both 5 hours and 29 hours following the completion of the protocol (Burd *et al.* 2010). Similarly, Terzis *et al.* (2010) showed a graded linear relationship in elevations of p70S6K and ribosomal protein S6 phosphorylation between 1, 3 and 5 sets of leg presses. Nonetheless, acute changes in myofibrillar protein synthesis should be analyzed cautiously as they poorly represent muscle protein accretion over time (Damas *et al*., 2016; Damas *et al*., 2015; Witard *et al*., 2021). Instead, it has been proposed that acute rises in myofibrillar protein synthesis following an RT bout are caused by an increased need of repairing and remodeling of the pre-existing fibres, and, potentially, to facilitate the future accretion of proteins (Damas *et al*., 2016; Damas *et al*., 2015; Witard *et al*., 2021).

The current literature on RTV seems to reach consensus on the presence of a reversed U-shaped relationship between RTV and hypertrophy, favouring the practice of HVRT, at least up to a certain threshold. This threshold is yet to be determined and might depend on certain characteristics of the individual, including their genetic background and the previous RTV performed (Roth *et al*., 2022). This relationship has been supported by a systematic review and meta-analysis conducted by Schoenfeld and his colleagues (2017) that showed, as weekly sets were divided in three different levels (< 5 sets/muscle group/week, 5-9 sets/muscle group/week and > 10 sets/muscle group/week), an effect favouring the practice of higher weekly sets/muscle group/week (p = 0.074). Additionally, no significant interaction between RTV and sex (p = 0.55), age (p = 0.66) and body segment (p = 0.28) were detected in their meta-analysis. Furthermore, they concluded that performing somewhere between 12 and 20 sets/muscle group/week was optimal for hypertrophy. Similarly, Remmert *et al*. (2025) showed diminishing returns at around 8.2 sets/muscle group/session. However, both studies mainly included randomized-controlled trials prescribing < 20 sets/muscle group/week and failed to identify a clear plateau for hypertrophy. On their side, Brigatto *et al.* (2022) showed that an 8-week protocol in men performed at 32 sets/muscle group/week led to greater increases in muscle thickness compared to their groups performing 16 sets/muscle group/week and 24 sets/muscle group/week. Observed increases for the biceps brachialis, triceps brachialis and vastus lateralis were about 3.1%, 7.0% and 9.4% for the 32-set group while the 24-set group and 16-set group observed increases of about 1.3%, 4.0%, 5.6% and 0.5%, 0.8%, 2.1%, respectively. Similarly, Schoenfeld *et al.* (2019) showed a graded-dose relationship between RTV and increases in muscle thickness between their three experimental group over the course of 8 weeks. Their HVRT group performed 30 sets/muscle group/week and 45 sets/muscle group/week for the upper limb and lower limb, respectively, while the two other groups performed 18 sets/muscle group/week and 27 sets/muscle group/week (for their moderate RTV group) and 6 and 9 sets/muscle group/week (for their LVRT group). On that note, a few limitations need to be considered when analyzing Schoenfelds' results: 1) A novel stimulus was potentially achieved by the prescribed RT plan as most of Schoenfelds' participants were not regularly achieving concentric failure in their respective routine while concentric failure was necessary in Schoenfelds' study, 2) The diet was not controlled for their study and their protocol only incorporated two 5-day diet recalls, which could have led to different macronutrients consumption among the experimental groups and 3) Muscle thickness increases reported (specifically the 0.72cm increase in mid-thigh muscle thickness) are far greater than those reported in literature and could result from an error in measurement or excessive muscle swelling and not hypertrophy *per se* (Buckner *et al*., 2023).

Briefly, current literature on RTV seems to favour the practice of HVRT protocols, both from a molecular standpoint and muscle size/FFM changes. Additionally, performing more than 12-20 sets/muscle group/week seems to induce greater hypertrophy, but up to an undetermined threshold. Finally, the administration of standardized RT protocols in a research context might not account for previous RTV, inducing interferences on the true role of RTV in FFM gain (Scarpelli *et al*., 2022). Based on the available literature, HVRT can induce greater hypertrophic changes, but up to an undetermined threshold.

Resistance training intensity. Firstly, it is important to distinguish between the global intensity of a given workout (subjective, the perceived exertion of an individual) and the intensities used throughout a workout (objective, the load, expressed as the percentage of 1 RM). In the following section, a focus will be held on the load as well as on concentric muscular failure, characterized as the incapacity to complete the concentric phase of a movement with proper form.

RTV and intensities are usually represented by a reversed relationship. According to the repetition continuum, the use of a high-repetition scheme requires the use of low loads (or intensities) while the use of a low-repetition scheme requires the use of high loads (or intensities) (Baechle *et* Earle, 2008). Thus, maximal strength gains are achieved while performing low-repetition and high-load schemes (< 5 RM) while hypertrophy is maximized using loads ranging from 6 RM to 12 RM (Baechle *et* Earle, 2008). This belief assumes that high loads are necessary to recruit the highest threshold motor unit and, therefore, recruiting as many muscle fibres as possible (Schoenfeld *et al*., 2017). Furthermore, this belief is also supported by the *size principle,* which dictates that, during a physical effort, the smallest motor units are recruited first, followed by the largest motor units (NCSA, 2021; Schoenfeld *et al*., 2017). If those statements were true, which is not the case, some modalities of training (aerobic exercise, for example) would not enhance hypertrophy (Konopka *et* Harber, 2014). Recently, the debate surrounding the necessity to use high loads (> 70% 1 RM) to optimize hypertrophy has been challenged by several authors. For example, following 12 months of detraining in men, a 6-week bench press protocol performed either at 30% 1 RM (to concentric failure) or at 75% 1 RM (for about 10 repetitions) led to similar increases in triceps brachialis (+9.8% and +11.9% for the low-load and high-load groups, respectively) and major pectoralis muscle cross-sectional area (+21.1% and +17.6% for the low-load and high-load groups, respectively) (Ogasawara *et al*., 2013). Of consideration, since a 12-month detraining phase was imposed to the participants, it is possible to compare their results to those seen in an untrained population. Similarly, in resistance-trained men, an 8-week RT protocol performed at either 8-12 repetitions or 25-35 repetitions (both to concentric failure) led to similar increases in muscle thickness for the elbow extensors (+6.0% and +5.2% for the high-load and low-load groups, respectively), the elbow flexors (+5.3% and +8.6% for the high-load and low-load groups, respectively) and the quadricep femoris (+9.3% and +9.5% for the high-load and low-load groups, respectively) (Schoenfeld *et al.*, 2015). Furthermore, a 2017 systematic review and meta-analysis compelling 21 studies concluded that low-load and high-load yield similar hypertrophy gains, with a study-level analysis showing no difference ($p = 0.56$) and the mean percentage of hypertrophy being similar between modalities (+8.3% and +7.0% for the high-load and low-load modalities, respectively). Finally, a 2021 review concluded that loads ranging from 30% 1 RM to 100% 1 RM would yield similar hypertrophy outcomes, independently of training status (untrained versus trained) and age (Schoenfeld *et al*., 2021). On that note, it remains possible, at least from a practical standpoint, that using moderate to heavy loads would be more efficient in inducing hypertrophy. Indeed, attaining concentric muscular failure seems necessary with lower loads, which might be difficult to attain given the intense discomfort induced by high-repetition schemes (Schoenfeld *et al*., 2021). Furthermore, performing high-repetition schemes for each set will take longer to complete than low-repetition schemes, which might not be suitable for everyone.

The debate surrounding the need to reach muscular failure has been ongoing for decades now. Characterized as the inability to complete the concentric portion of a repetition with proper form, concentric failure has been thought to generate greater hypertrophic outcomes than nonfailure sets by recruiting all high-threshold motor units (Lasevicius *et al*., 2022). A certain consensus in the literature has been reached as low-load and high-repetition RT schemes should be performed to concentric failure to maximize hypertrophy. In high-load low-repetition scheme, longitudinal studies are showing evidence both for (Drinkwater *et* al., 2005) and against (Sampson *et* Groeller,

2016) concentric failure. When comparing those methods, one key point needs to be considered: when equalled to the number of repetitions performed, performing a set to concentric failure leads to a greater VL performed, cofounding the influence of concentric failure on hypertrophy. Moreover, from a practical standpoint, performing a few sets to concentric failure might help chronically trained individuals breaking plateaus, while performing all sets to concentric failure would most likely lead to high levels of fatigue. On that note, a 2022 longitudinal study conducted in untrained men compared 4 different RT routine: high-load to failure, high-load to non-failure, low-load to failure and low-load to non-failure with VL matched between groups (Lasevicius *et al*., 2022). Following the 8-week RT plan, all groups increased their vastus lateralis muscle thickness, but the low-load to non-failure group showed smaller hypertrophy changes compared to the other groups. Additionally, muscle thickness was similar between the high-load to failure, high-load to non-failure and low-load to failure groups. Similarly, a 2022 systematic review and meta-analysis conducted by Grgic *et al*. (2022) concluded that training to concentric failure provides no significant advantage compared to non-failure training. Of consideration, a subgroup analysis in resistance-trained individuals favoured training to concentric failure, but those results need further support since only two of the included studies were conducted in resistance-trained individuals.

To resume, a wide range of intensities can be used to optimize muscle growth, at the opposite of the traditional repetition continuum. Indeed, both higher and lower repetition schemes can be used to optimize hypertrophy, but high-repetition schemes might not be as time efficient nor as pleasant to perform. Furthermore, training to concentric failure might not be necessary to optimize muscle growth, at least in untrained individuals and with lower repetition schemes. However, more studies are needed in resistance-trained individuals to support this hypothesis.

Resistance training frequency, rest times and tempo. In the following section, the contribution of frequency (number of sessions/muscle group/microcycle), resting time (resting time between sets) and tempo (the duration of a repetition, including the duration of the eccentric and concentric contractions and the transition phases between them) to hypertrophy will be briefly discussed.

The premise underlying the practice of higher RT frequencies in resistance-trained individuals is primarily based on the blunted MPS response following an RT bout in that population, which lasts about 24 hours (Schoenfeld *et al*., 2021). Therefore, frequent spikes in MPS during a week would potentially lead to greater potential for MPS to surpass MPB, and thus hypertrophy. Furthermore, as a training session goes, an individual is going to experience increased fatigue levels, leading to a decrease in strength output throughout the session. Of consideration, increasing RT frequency may concomitantly increase the VL performed, which is known to be a driver of hypertrophy. To isolate the true role of frequency, Saric *et al*. (2019) conducted a randomized-controlled trial in resistance-trained men where their subjects underwent an equalled VL program with a frequency of 3 sessions/week or 6 sessions/week using a full-body split. By the end of the intervention, no difference was seen between both groups as they both similarly increased their muscle thickness (Saric *et al*., 2019). Additionally, a 2021 position stand by the *International Universities Strength and Conditioning Association* on the role of frequency in muscle hypertrophy supports the hypothesis that frequency is not a direct driver for hypertrophy *per se* but increases in VL resulting from an increased frequency may be the reason higher frequencies enhance hypertrophy.

Rest times correspond to the duration of one's break following a given set. Currently, the American College of Sports Medicine recommends rest intervals of about 30 to 90 seconds to elicit hypertrophy (NCSA, 2021). Additionally, rest times can be categorized in two categories: complete rest times (from 3 minutes to 8 minutes) and incomplete rest times (less than 3 minutes) (de Camargo *et* *al*., 2022). This categorization has been based on the time required to "completely" re-synthetize phosphocreatine stocks (to about 70% to 80% of its initial stocks), which are the primary energetic contributors to short-term efforts (RT set, for example) (NCSA, 2021; Schoenfeld, 2020). Thus, one might think that longer rest intervals are necessary for an optimal strength output during a given set, which may result in a greater VL performed and increased hypertrophy. On the other hand, shorter rest intervals (approximately 1 minute) have been recommended to maximize muscle hypertrophy. This recommendation was based on acute growth hormones release studies, which showed that following shorter rest intervals, greater acute blood releases in growth hormones happened compared to longer rest intervals (NCSA, 2021). On that note, a few points need to be clarified concerning the premises favouring the use of longer and/or shorter rest intervals: 1) If a complete re-synthesis of phosphocreatine stocks was necessary to optimize muscle growth, professional bodybuilders using rest intervals of 60-90 seconds would not display substantial amounts of muscle mass (at least in drug-free athletes) and 2) The contribution of growth hormones to muscle hypertrophy has been largely investigated, yet they do not enhance hypertrophy, at least when secreted endogenously (Fink *et al*., 2018 ; NCSA, 2021). To clarify the role of rest times on muscle hypertrophy, Longo *et al.* (2022) used a within-subject design, assigning its participants' legs to either a 60-second rest interval with equated VL, a 60-second rest interval without equated VL or similar groups using a 180-second rest interval. Sets were performed at 80% 1 RM on the inclined leg press, 2x/week for a 10-week period. By the end of the study, all groups increased their quadriceps cross-sectional area, but increases were significantly greater among the groups who performed higher VL, regardless of the rest intervals. Recent data from a systematic review and meta-analysis suggest a small benefit to the usage of longer rest intervals for hypertrophy (> 120 seconds) (Singer *et al*., 2024) but some questions remained to be answered. First, most studies included in their analysis were conducted in untrained individuals, which are known to be less tolerant to high degrees of effort and intensities (NCSA, 2021). Therefore, shorter rest intervals might not be suitable for them. Second, the protocols of the included studies were quite different, as multi-joint exercises, larger muscle groups and free-weights exercises are more susceptible to benefit from longer rest intervals compared to single-joint exercises, smaller muscle groups or machines/cables. Lastly, longer rest intervals (> 120 seconds) might not be feasible for everyone since it may increase the duration of a session. Therefore, one aiming to optimize hypertrophy might benefit from the incorporation of both longer rest intervals, specifically for larger muscle groups (quadriceps, for example) or multi-joint exercises (deadlift, for example) and shorter rest periods (for smaller muscle groups or single-joint exercises). Thus, rest times of about 90 seconds seem to be a good trade-off between time efficiency and hypertrophic outcomes.

Lastly, the tempo can be seen as the duration of a whole repetition, more specifically the duration of the eccentric portion, the concentric portion and the phases between those muscle contractions. There are two types of tempo movement: 1) Intentional tempo (which can be described as a periodized time adjustment of a given repetition) and 2) Unintentional tempo, which typically occurs when lifting heavy loads (slow movement caused by heavy charge or fatigue accumulation) (Wilk *et al*., 2021). Typically, tempo is prescribed as a 4-digit code (2-0-2-0, for example), where the numbers represent the duration of the eccentric, eccentric-isometric, concentric and concentric-isometric portions of a movement (Wilk *et al*., 2021). Of consideration, modifications of the tempo directly impact the TUT, the load and the number of repetitions performed (Wilk *et al*., 2021). For example, eccentric muscle contractions are about 20%-50% stronger than concentric contractions, which means that slower eccentric contractions are easier to achieve than slower concentric contractions (thus providing a greater TUT and consequent advantage for hypertrophy) (Schoenfeld *et al*., 2017). Therefore, when analyzing the role of tempo in hypertrophy, it is important to isolate it from the other variables as a greater TUT or greater VL may act as covariables and induce hypertrophic changes. Furthermore, adjusting the duration of a specific contraction can affect hypertrophy outcome, as slow eccentric movements have been shown to induce greater increases in muscle mass than slow concentric contractions (Carrasco *et al*., 1999; Suchomel *et al*., 2019). According to a 2015 systematic review and meta-analysis, a duration of 0.5 second to 8 seconds seems to be optimal for hypertrophy while repetition duration above 10 seconds is unlikely to induce greater hypertrophy (Schoenfeld *et al*., 2015). Even though the range recommended by Schoenfeld *et al*. (2015) is wide, they did not investigate whether a certain duration of certain phases would lead to greater hypertrophy. Additionally, Schoenfeld *et al*. (2017) showed that eccentric contractions may provide greater increases in muscle mass than concentric contractions (+10.0% versus +6.8%), but failed to reach statistical significance (Schoenfeld *et al*., 2017). To fulfill this gap, Wilk *et al*. (2021) conducted a systematic review but the findings were inconclusive regarding whether slower or faster eccentric and/or concentric contractions would enhance hypertrophy. On that note, they did suggest that the eccentric portion of a movement should be slower than the concentric portion. This could be explained by a greater strength production while a muscle is lengthened, therefore increasing TUT and thus hypertrophy (NCSA, 2021; Schoenfeld, 2020). However, many of the included studies in Wilks' review used body composition assessment methods (such as air displacement plethysmography) instead of direct measurements of hypertrophy. More recently, a review concluded that repetition duration should range somewhere between 2 and 8 seconds and that the duration of each phase is not of particular interest, as long as the eccentric portion is executed in a controlled manner (Androulakis *et al*., 2024)

To summarize, frequency *per se* is not a direct modulator of muscle mass, but changes in VL related to higher or lower frequencies are. Furthermore, rests of about 90 to 120 seconds seem optimal for hypertrophy, but shorter rest times can also be used for smaller muscle groups or while being time restricted. Finally, the tempo used while performing a set does not seem to matter, contrary to the belief that longer repetitions would lead to greater hypertrophy. On that note, controlling the weight lifted during a set might be of primary importance for repetitions lasting 2-8 seconds, while extremely fast (< 1 second) or slow repetitions (> 8 seconds) might mitigate hypertrophy.

Macronutrient Composition for Fat-Free Mass Sparing and Performances

As previously mentioned, dietary interventions alone lead to about 25% of BM losses in FFM (Weinheimer *et al*., 2010). Therefore, it is important to recognize which nutritional changes can be used to optimize FFM retention and performance. The following section will give an overview of the current dietary practices allowing FFM maintenance under CR.

The extent of FFM losses during CR is influenced by several factors, such as one's initial FM levels (Elia *et al*., 1999), the magnitude of the CR and associated rates of weight losses (Garthe *et al*., 2011), and the macronutrient composition. Elia and his colleagues (1999) reported that individuals living with overweight (ILWO) rely less on endogenous body protein to sustain basal metabolic rate (2 to 3-fold less nitrogen excreted compared to their leaner counterparts). This correlates with the smaller FFM changes observed in ILWO during a CR, suggesting that greater FM levels preserve FFM under conditions of CR. Similarly, larger CR has been consistently associated with greater FFM losses, both in normal-weight individuals and ILWO (Garthe *et al*., 2011; Vink *et* al., 2016). Macronutrient manipulation, such as protein intake, represents a strategy that might help reduce FFM losses. The American College of Sports Medicine recommends intake from 1.2g-1.7g/kg BM under EB for athletes, with intakes near the upper limit suggested to maximize hypertrophy. Nonetheless, Morton and colleagues (2018) showed a plateau for hypertrophy with intake > 1.6g/kg BM when combined with RT and under EB (Morton *et al*., 2018). While no clear recommendation currently exists regarding protein intake under CR, protein requirements likely increase to resensitize MPS (Hector *et* Phillips, 2018). This is critical since reduced MPS coupled with increased/constant MPB would accelerate endogenous protein breakdown, and therefore FFM losses. Moreover, engaging in regular exercise practice during CR may further elevate protein needs to support FFM reconstruction and preservation (Philipps *et* Van Loon, 2013). In recreationally active men, 2.4g/kg BM resulted in FFM gain despite being under a +/- 40% CR, likely reflecting increased MPS and/or reduced MPB (Longland *et al*., 2016). In athletes living with slight overweight, a 6-week – 25% CR produced no significant difference in FFM changes between 0.8g/kg, 1.6g/kg and 2.2g/kg protein intake (Kanaan *et al*., 2025). Of note, in males having 10% less FM than Kanaan *et al*., (2025)'s cohort, a 2.3g/kg protein intake during a 40% CR resulted in non-significant losses in FFM (Mettler *et al*., 2010). Collectively, evidence from Phillips and Van loon (2013), Helms *et al.* (2014) and Hector and Phillips (2018) suggests that protein intakes of about 1.8g-2.7g/kg BM, 2.3g-3.1g/kg FFM and 1.6g-2.4g/kg BM during CR are necessary to mitigate FFM losses. In support of their recommendations are the results from Refalo *et al*. (2022), who found a positive linear relationship between protein intake and FFM changes up to 3.2g/kg BM during CR in normal-weight resistance-trained individuals (Refalo *et al*., 2022).

Regarding the impact of protein intake on performance during CR, available evidence remains scarce. In resistance-trained individuals under EB, a 10-day high-protein diet (2.9g/kg BM) did not enhance squat performance, creatine kinase levels or muscle soreness compared to a 1.8g/kg BM intake (Roberts *et al*., 2017). However, their findings should be analyzed cautiously since a small sample size was used (n = 14). What is more, the short duration of their dietary intervention may not represent long-term performance changes induced by higher protein intake. Finally, their results are somewhat like those obtained by Morton *et al*., (2018), who showed that intakes of 1.6g/kg BM are sufficient for resistance-trained individuals. In contrast, Helms *et al*. (2015) found that 2.8g/kg BM protein intake in weightlifters improved mood but slightly reduced strength compared to a 1.6g/kg BM intake (Helms *et al*., 2015). Both groups were matched for carbohydrate intake while fat intake for the high-protein group was about 15% of the total energetic intake. Of consideration, it has been recommended to not consume less than 20% of total energetic requirements in fat as it may induce a disruption in androgen production and liposoluble vitamins absorption (Helms *et al*., 2014; Marieb *et* Hoehn, 2007). Knowing that androgens play a major role in performance (NCSA, 2021), the decreases in strength for the high-protein group showed in Helms' study (2015) may have been in part driven by an insufficient fat intake.

In addition, the balance between carbohydrate and fat intake plays a key role in preserving FFM during CR. Altering macronutrient proportions has been shown to affect protein oxidation under EB. For example, a high-fat/low-carbohydrate diet decreased glucose oxidation rate while increasing protein oxidation rate from 7.6g +/- 0.7g / 120min to 13.4g +/- 2.8g / 120min (Haman *et al*., 2004). Under starvation, the contribution of protein to basal metabolic rate can rise markedly, accounting for as much as 30% of energy requirements in normal-weight individuals (Elia *et al*., 1999). Both CR and low carbohydrate intake therefore elevate protein oxidation, thus heightening the risk of FFM losses. During exercise, the relative contributions of carbohydrate and fat to adenosine triphosphate production depend on the modality (RT versus aerobic), as well as to the intensity and duration (Lim *et al*., 2022; Parolin *et al*., 1999). At high-intensity aerobic exercise (about 85% of maximal oxygen consumption), glycolytic sources (plasma glucose and muscle glycogen) supply more than half the energy demand (Farinatti *et al*., 2016; Haman *et* *al*., 2004 ; Melzer, 2011). During RT, phosphocreatine and muscle glycogen are the predominant energy substrate (Melzer, 2011). Accordingly, reducing carbohydrate intake would likely compromise both FFM preservation and power/strength-related performances. This is supported by Horswill *et al*. (1990), who found that male wrestlers reducing BM by 6% over two separate 4-day periods achieved greater arm-cranking power with a high-carbohydrate diet (66% of energy intake [EI]) compared to a low-carbohydrate diet (42%) (Horswill *et al*., 1990). Likewise, Hsu *et al*. (2023) reported that taekwondo athletes undergoing a 7-day CR with a low-carbohydrate diet (10% of EI) experienced significantly higher fatigue than those on a moderate-carbohydrate diet (60%) (Hsu *et al*., 2023). Interestingly, FM and body fat percentage significantly decreased in the moderate-carbohydrate group, while a non-significant decrease was observed in the low-carbohydrate group.

In summary, increasing proteins intakes to about 1.6-2.4g/kg BM seems necessary to maintain MPS and/or diminish MPB, therefore maintaining FFM while undergoing CR. Current evidence also suggests that decreasing fat intake rather than carbohydrates can maintain RT performances. The relationship between protein intake and performances under CR is yet to be elucidated. Nonetheless, fat intake should not represent less than 20% of the total caloric intake as it may induce disruption in androgen production, lack of essential fatty acids and impairments in fat-soluble vitamin absorption (Helms *et al*., 2014; Marieb *et* Hoeln, 2007).

Resistance Training Volume and FFM Sparing Under Caloric Restriction

As previously mentioned, HVRT is thought to induce greater gains in FFM, at least under mass-stable condition. Based on those studies, the hypothesis that HVRT would yield greater FFM maintenance remains possible. In sedentary ILWO, preliminary data shows that a brisk walking routine performed 5 times/week with a progression in volume (from 3 miles to 6 miles) and in intensity (from 65% to 80% of maximal heart rate) led to a slight gain (+0.37kg) in FFM despite being under a 1200kcal/day CR (Powell *et al*., 1994). As previously mentioned, cardiovascular activities have the capacity to induce hypertrophy (Ggric *et al*., 2019), which might have been enhanced by the progression model used in their study. Furthermore, those results might also be explained by the unusual mechanical constraints caused by the volumes and intensities used since their participants were not physically active prior to the commencement of the study. Therefore, RT might not be necessary for sedentary ILWO aiming to maintain their FFM under CR. Similarly, in recreationally active ILWO, a combination of 2.4g/kg BM/day and a practice of 6 workout sessions/week was able to increase FFM by 1.2±1kg despite their participants undergoing a 40% CR (Longland *et al*., 2016). Of consideration, RTV was not the controlled variable in their study. Additionally, their exercise intervention incorporated a multitude of modalities (RT, high-intensity interval training, plyometrics, a 250-kilojoule time trial and a minimum of 10,000 steps/day), which could have helped promote a better maintenance of FFM by providing different stimuli. To the best of our knowledge, only two studies conducted in a resistance-trained population were specifically seeking differences in FFM during CR by manipulating RTV. To begin with, Roth and his colleagues (2023) conducted a 6-week randomized-controlled trial in resistance-trained men, dividing their participants in two groups: an HVRT group, performing 20 sets/muscle group/week and an LVRT group, performing 12 sets/muscle group/week. Their participants underwent a 30kcal/kg CR with a protein intake settled at 2.8g/kg FFM. By the end of the intervention, the HVRT group lost 1.69 ± 1.12kg and 0.51 ± 2.30 kg in BM and FFM, respectively, while the LVRT group lost 1.76 ± 1.76 kg and 0.92 ± 1.59 kg in BM and FFM, respectively. Losses in FFM were significant in both groups *(p* = 0.022), but not different between them (*p* = 0.966), suggesting that RTV is not of primary importance while undergoing CR. Nonetheless, this study presents a few limitations that need to be addressed. Firstly, reported FFM losses are within the margin of error of the bioelectrical impedance, which is about ± 0.9kg (Siedler *et al*., 2021). Secondly, according to a meta-analysis, 12 sets/muscle group/week is considered HVRT (Schoenfeld *et al*., 2017). Therefore, both groups underwent an HVRT intervention, which leaves a gap concerning the influence of LVRT (< 5 sets/muscle group/week) and moderate RTV (5-9 sets/muscle group/week) on FFM under CR. Thirdly, the RTV prescribed for the HVRT are within the current American College of Sports Medicines' recommendations for resistance-trained individuals (under EB), which are to perform somewhere between 4 and 6 sets/exercise (or 10-20 sets/muscle group/week). Yet, it remains possible that RTV above those recommendations are necessary under CR. Fourthly, the prescribed CR resulted in an average loss of less than 2kg BM among their participants over the course of 6 weeks. Considering that the prescribed CR was light-to-moderate, it remains possible that LVRT was sufficient to spare FFM under those conditions. In fact, rates of weight loss of 0.7%/week have been shown to result in less FFM losses and decrements in performances than weight loss rates of 1.4% (Garthe *et al*., 2011). Also, the methods used in their study did not incorporate the DXA scan nor deuterium oxide, which are considered gold standards for body composition and total-body water assessments, respectively (Bila *et al*., 2016; Bilsborough et al., 2014). Despite those limitations, a case study on a female bodybuilder preparing for a contest showed, using a similar set range of about 10-20 sets/muscle group/week, an increase in FFM of 1.1kg while losing 7.4% in BM (Tinsley *et al*., 2019). Again, Tinsleys' participant presented a baseline FM percentage about 2% greater than Roths' participants, potentially contributing to the observed gain in FFM. Furthermore, her RT programs lasted (on average) about 3 weeks while her repetition range was quite wide (3 to 40 repetitions per set), which could have helped the preservation of a novel stimulus. In contrast, a review concluded that decreasing RTV during a CR was more likely to induce losses in FFM (Roth *et al*., 2022). On that note, none of the studies included in their review was specifically seeking differences in FFM changes between different RTV. Furthermore, only 15 studies were included in their analysis, with 11 studies using a combination of different modalities of training (aerobic and RT), which could have interfered with the anabolic effects of RT on FFM. Based on these two studies and their limitations, it remains difficult to clearly establish whether HVRT could elicit a greater maintenance of FFM under CR. Interestingly, a study conducted in male bodybuilders during their preparation for a natural show reported a slight gain in FFM (71.4kg ± 8.9kg to 71.8kg ± 9.1kg) when increasing the VL from 82 500kg ± 34 600kg to 94 300kg ± 44 200kg while a decrease in VL (94 300kg ± 44 200kg to 66 600kg ± 42 000kg) led to a significant decrease in FFM (71.8kg ± 9.1kg versus 70.9kg ± 9.1kg) (Mitchell *et al*., 2018). Nonetheless, details about the exercises, RTV (in sets) and intensities used by the bodybuilders were lacking, making it hard to conclude whether the FFM gains were caused by an increase in sets/muscle group/week performed or by an increase in tonnage. Furthermore, their results are showing evidence against the belief that athletes should reduce their RTV while undergoing CR to limit fatigue levels, preserve performances and FFM. Similar results were obtained by Van der Ploeg *et al*. (2001) and Vargas-Molina *et al*. (2020) as they both found losses of FFM in women resistance-trained athletes who decreased their RTV throughout their respective RT plan.

When looking at current literature, a gap remains to be fulfilled concerning the influence of RTV on FFM maintenance under CR. Most studies conducted under CR did incorporate an RT component but were not specifically looking at the outcomes caused by manipulating RTV. Furthermore, many of these studies used a combination of different modalities of training, which may have interfered with the prescribed RTV. Finally, many studies lacked details about the previous RTV performed, yet prescribing an RT plan in a research context while not accounting for the previous RTV may induce a decrease or increase in VL and subsequently interfering with the prescribed RTV.

Resistance Training Volume and Performances Under Caloric Restriction

The premise behind incorporating an HVRT routine to maintain performances holds on correlational data between muscle size and strength/power. The larger a muscle is, the greater the force production should be (NCSA, 2021). In fact, as much as 35% of strength increase over an 8-week period can be attributed to hypertrophy (Loenneke *et al*., 2017). Therefore, if FFM decreases during CR, it may induce strength and power losses. Inversely, performing an HVRT routine during a CR may exacerbate the perceived levels of fatigue, which may negatively affect force and strength production. To date, the only randomized-controlled trial on the influence of RTV on FFM sparing and strength production showed no difference in leg press strength gains between two groups of resistance-trained men performing either 12 sets/muscle/week or 20 sets/muscle group/week ($p > 0.05$) despite losing a significant amount of FFM (Roth *et al*., 2023). Indeed, their HVRT group gained about 31.65 kg of strength while their LVRT group gained about 35.56 kg ($p < 0.001$), with no difference between groups ($p > 0.05$). Additionally, the VL was significantly greater among the HVRT, suggesting that the VL performed is not a primary driver of strength gains. Similar results were obtained under EB as 45 sets/muscle group/week lead to similar strength gains to 9 sets/muscle group/week (Schoenfeld *et al*., 2019). Interestingly, Roths' analysis showed no difference between their groups in terms of sleep duration, sleep onset, fatigue, anxiety/depression, vigor and hostility (Roth *et al*., 2023). Taken together, those results suggest that: 1) HVRT is not necessary for strength gain or maintenance under CR and 2) Performing HVRT under CR is not necessarily inducing greater fatigue levels and might therefore be sustainable. Interestingly, a case study conducted over the course of a bodybuilding contest preparation in a man bodybuilder showed a 26% gain in maximal isometric strength (of the knee extensor) but an 18% decrease in maximal height on the vertical jump (Schoenfeld *et al*., 2020). Over that 8-month period, the participant lost 10.3kg in BM and 5.8kg of FFM despite practicing an HVRT routine (5-6 RT sessions/week, 10-14 exercises/session and 3-4 sets/exercise). Of consideration, prior to the beginning of the study, the subject was already presenting low levels of adiposity (less than 10% FM), which could explain why most of the BM lost is attributable to FFM losses. Again, those results suggest that: 1) Strength gains during CR are possible, even when substantial amounts of FFM are lost and 2) Velocity and power might be more affected by CR than other muscular qualities (such as strength). Similarly, in elite judokas men, 15 days – 40% CR induced a significant decrease in both FFM (66.8kg ± 3.2kg pre-intervention to 65.8kg ±3.6kg) and performances for the Special Judo Fitness Test (Lalia *et al*., 2019). However, details about the RT parameters are lacking as the participants were instructed to maintain their normal RT routine throughout the intervention. Additionally, their participants significantly reduced their protein intake during the intervention (150g ± 11g pre-intervention to 87g ± 7g post intervention), which could have led to a non-sufficient protein intake during the CR, thus increasing FFM and performance losses.

Current evidence suggests that some muscular qualities (power and velocity) may be negatively affected by CR while others (strength) can be maintained or even improved, independently of FFM losses. To this day, only one study directly investigated differences between different RTV on strength, yet their results suggest that both HVRT and LVRT can be effective at improving strength during ED. Nonetheless, maintaining the same RT routine during CR seems to negatively affect performances. Therefore, more studies are needed to determine whether HVRT can induce greater strength maintenance or improvements than LVRT during CR. Additionally, the relationship between FFM changes and performances during CR remains to be clarified.

Conclusion

Athletes and resistance-trained individuals undergo CR for a multitude of reasons, including improvements in power-to-weight ratio and aesthetics. Those changes are achieved by decreasing BM and FM levels, but FFM losses have been reported in literature and seem to be dependent on a multitude of factors (initial FM levels, magnitude of the CR and consequent rates of weight loss, macronutrient composition, etc.). It has been recommended to increase protein intake to about 1.6g-2.4g/kg BM and to perform RT to reduce FFM losses, but how RT should be performed under CR has not been elucidated yet. Indeed, HVRT has been shown to induce greater increases in FFM than LVRT in a resistance-trained population under mass-stable conditions. However, the only randomized-controlled trial comparing different RTV under CR showed no difference in FFM changes between a 12 sets/muscle group/week and a 20 sets/muscle group/week protocol. Thus, if a clear linear relationship exists between FFM and strength, decreases in FFM during CR would directly reduce strength output, yet many found that strength could improve despite FFM losses. Finally, while analyzing the current body of literature, it remains important to acknowledge the limitations of certain instruments as changes in FFM can reflect both changes in protein content and changes in total-body water. For those reasons, it remains unclear whether HVRT could elicit a greater maintenance of FFM and strength performances under CR in a resistance-trained population.

Study Objectives

This study had two objectives. The main objective was to determine whether higher RTV could reduce FFM losses to a greater extent than lower RTV. The second objective was to determine if higher RTV could facilitate the maintenance of strength performances compared to lower RTV.

Study Hypotheses

We hypothesized that HVRT (30 sets/major muscle group/week) would promote a greater FFM maintenance under CR compared to LVRT (12 sets/major muscle group/week). Similarly, we hypothesized that HVRT would result in greater increases in strength compared to LVRT.

Chapter 3: Methods, Results and Discussion

Given the format of the thesis is by article, the section describing the Methods, Results and their Discussion is presented in the format of a scientific paper. This is done to avoid redundancy. Of note, this article is currently under review by the *European Journal of Clinical Nutrition*.

A 4-week caloric restriction with High Volume Resistance-Training and High-Protein Diet Does Not Increase Fat-Free Mass Sparing but Increases Strength

Samir Nait-Yahia, Mikael F. Kanaan, Noémie Beauregard, Merissa Jade Anderton, Andrea Duval, Éric Doucet

School of Human Kinetics, Faculty of Health Sciences, University of Ottawa, Ottawa, Ontario, Canada, K1N 6N5

Send correspondence and reprint requests to:

Éric Doucet, Ph.D.
School of Human Kinetics,
University of Ottawa, Ottawa (On), Canada, K1N 6N5

E-mail: edoucet@uottawa.ca

Abstract

Background

Athletes employ weight loss protocols to lower fat mass (FM) and maintain fat-free mass (FFM) for performance purposes. High-volume resistance-training (HVRT) has been associated with greater increases in FFM than low volume resistance-training (LVRT). However, less is known about the effects of HVRT under caloric restriction (CR). Therefore, it remains unclear whether HVRT could elicit greater retention of FFM and improvements in strength during CR.

Objectives

Determine the effects of HVRT and high protein intake on FFM and strength in resistance- trained individuals after a 40% CR.

Methods

Sixteen resistance-trained individuals underwent a high-protein (2.3g/kg body mass (BM)), 4-week 40% CR with a 5-day/week resistance-training intervention. Participants were randomly assigned to LVRT (12 sets/muscle group/week) or HVRT (30 sets/muscle group/week). Pre-post intervention testing included dual energy x-ray absorptiometry, indirect calorimetry, dietary records, resistance-training records, 5RM strength testing and nitrogen balance.

Results

Significant reductions in BM ($\Delta - 4.2 \pm 0.5$ kg, $p < 0.001$), FM ($\Delta - 3.7 \pm 0.4$kg, $p < 0.001$) and %FM ($\Delta - 3.5 \pm 0.4\%$, $p < 0.001$) were observed, but changes were not different between groups. No intervention or group by intervention effects were noted for FFM. HVRT produced greater increases for 5RM testing for chest press ($p = 0.005$), right leg press ($p = 0.003$) and left leg press ($p < 0.001$).

Conclusion

HVRT does not seem to further enhance FFM retention during a 40% CR. Albeit, greater increases in strength were noted in HVRT, but mechanisms underlying such improvements remain to be investigated.

Key words: Resistance-Training Volume, Caloric Restriction, Body composition, Strength, Resistance-Trained Individuals

Introduction

Caloric restriction (CR) and exercise are commonly used to reduce fat mass (FM) and to increase or maintain fat-free mass (FFM) [1, 2]. The latter are often employed by athletes who seek to increase power-to-mass ratio, which has been associated with improved physical performance [3, 4]. However, CR is also reported to induce FFM losses [2, 4], which may result in performance decrements [5].

Losses of FFM during CR may be exacerbated by different factors, including low initial adiposity [6] and longer and/or more severe CR [7]. Such decreases in FFM may ultimately be detrimental to athletes seeking improved performance through an increased power-to-mass ratio since higher levels of FFM have been associated with greater force and power production [8].

Both dietary manipulations and the incorporation of resistance training (RT) have been found to mitigate FFM losses during CR [5]. In individuals living with overweight or obesity, dietary interventions alone normally produce FFM losses of about 25% of the body mass (BM) lost, while combining dietary interventions with RT reduced those losses to approximately 11% [9]. What is more, protein intakes of about 2-3x the current recommended dietary allowance (RDA) have been suggested to also lessen FFM losses [10]. Those recommendations are based on the premise that an increased protein intake could restore the reduced muscle protein synthesis (MPS) response following RT during periods of CR [10]. However, we recently demonstrated that intakes as low as 1.2g/kg BM were equivalent to 2.2g/kg BM in the sparing of FFM in recreational athletes [11]. Of consideration, our intended deficit of 25% was not achieved (and determined to be ~12%). Hence, larger deficits may necessitate more protein to prevent the loss of FFM. Interestingly, Longland *et al.* [1] demonstrated that protein intakes of 1.2 and 2.4g/kg BM could both induce FFM gain in recreationally active men undergoing a 4-week 40% CR, but changes in FFM were significantly greater with protein intakes of 2.4g/kg BM. Lastly, Mettler *et al.* [2] showed that protein intakes of 1 and 2.3g/kg BM were unable to prevent FFM losses in resistance-trained men undergoing a 40% CR, but losses were significantly greater among the 1g/kg BM group. Taken together, those results suggest that increased protein intake may have a sparing effect on FFM for leaner individuals during more severe CR.

RT has been shown to attenuate FFM losses during CR [5, 11]. However, less is known about training volume and its effect on FFM retention. It has previously been suggested that RT volume (RTV) is the main driver of muscle hypertrophy, and that high volumes resistance-training (HVRT) usually correlate with higher increases in FFM [12-15]. Operationally defined as the number of sets/muscle group/week or in volume load (repetitions x load) [13], HVRT have long been thought to induce greater hypertrophy than low volume resistance-training (LVRT), at least in mass stable individuals who are in energy balance. For instance, previous meta-analyses by Schoenfeld *et al.* [14]and Remmert *et al.* [16] revealed a reversed u-shaped relationship between hypertrophy and RTV, with the latter observing diminishing returns around 8.2 fractional sets/muscle group/session. However, both meta-analyses did not reveal a clear ceiling effect and lacked studies that included > 20 sets/muscle group/week, leaving a gap regarding such high volumes on hypertrophy. What is more, most of the studies included in the latter [14, 16] were conducted in untrained individuals. Finally, less is known regarding the effects of RTV on FFM retention under CR [17]. To date, the only randomized-controlled trial conducted that investigated differences in RTV (20 vs. 12 sets/muscle group/week) during CR (33% CR) revealed no differences in FFM retention in men over a 6-week period [18]. Therefore, more research is needed to clarify if changes in hypertrophy in response to HVRT seen under energy balance are also applicable to periods of CR.

The primary aim of this study was thus to determine whether HVRT (30 sets/muscle group/week) could reduce FFM losses to greater extent than LVRT (12 sets/muscle group/week) in resistance trained athletes with a protein intake of 2.3 g/kg BM. We also investigated whether 30 sets/muscle group/week would impact strength performance to greater extent than 12 sets/muscle group/week. It was hypothesized that 30 sets/muscle group/week would be superior at both reducing FFM losses and strength decrements than 12 sets/muscle group/week.

Methods

Population

Eighteen participants were recruited for this study. Sixteen completed the intervention and all testing sessions (14 males, 2 females, aged 23.9 ± 3.7 years). Two participants dropped out after baseline testing and were not included in the analyses. Reasons for dropping out included time constraints (n =1) and reasons unrelated to the study (n =1). Participants were recruited through ads displayed at the University of Ottawa and through social media publications. Inclusion criteria included: 1) resistance-trained individuals, defined as individuals performing any form of resistive exercise (weights, kettlebells, resistance bands, calisthenics); 2) aged 18-35, 3) with a minimum RT experience of 3 sessions/week for at least 12 months. Exclusion criteria included: 1) individuals who purposefully lost BM prior to the study (> 3 months); 2) individuals living with a health condition that could have been aggravated by our protocol; 3) individuals consuming anabolic steroids or recreational drugs (with the exception of alcohol) and 4) individuals who could not engage in a 5-day/week RT routine. Our participants came from different sporting backgrounds including rugby, basketball, ice hockey, and volleyball.

Study Design

We conducted a 4-week intervention where participants were randomly assigned to either a (1) HVRT group (30 sets/major muscle group/week) or a (2) LVRT group (12 sets/major muscle group/week) as shown in **Figure 1**. Both groups were subjected to a 40% energy restriction for 4 weeks while also consuming 2.3 g/kg BM of protein. Sport-specific practices were allowed, but performing RT outside of the prescribed plans was proscribed, including sport-related RT. This study was conducted according to the guidelines laid down in the Declaration of Helsinki and the University of Ottawa Ethics Committee approved all procedures involving human subjects (H-01-24-9926). Written informed consent was obtained from all participants.

Nutritional Intervention

Participants were asked to wear an accelerometer (Sense Wear Pro 3 Armbands©, HealthWear-Bodymedia, Pittsburgh, PA, USA) for 3 days after the first experimental testing session, as done previously [11]. The accelerometers provided estimates of energy expenditure (EE) in kcal for activities performed at ≤ 3 METS and activities performed at ≥ 3 METS. Only the latter was used in our estimations. A 3-day average was used as a proxy for daily non-resting energy expenditure (NREE). Estimates of NREE (obtained by accelerometry) were combined to resting energy expenditure (REE) (assessed by indirect calorimetry (see below)) and the thermic effect of food (TEF) (estimated as 10% of the total energy expenditure) [19] to obtain an approximation for total daily energy expenditure (TDEE). Participants were provided with a diet plan based on their estimated TDEE as previously described (11). TDEE was determined using the following equation:

1. TDEE = (REE + NREE) *1.1 (to account for TEF)

A 40% reduction was applied to TDEE in order to obtain the energy intake (EI) for the dietary intervention using the following equation:

2. EI = TDEE * 0.6

The macronutrient composition employed of diets for both groups consisted of the following: 2.3g/kg BM from protein, 20% of EI from fat and the remainder from carbohydrates. For example, a 70kg individual with a TDEE of 2500kcal was prescribed a 1500kcal diet plan containing 33g (20%), 161g (43%), and 139g (37%) of fat, protein and carbohydrate, respectively. Alcohol consumption was allowed (two standard drinks/day), but participants were advised to maintain alcohol consumption to a minimum during the intervention. Briefly, our food plans were based on the food exchange system from the Canadian Diabetes Association. This system categorizes foods into 7 groups (dairy, meat & substitutes, fats, bread & whole grains, fruits, vegetables and condiments including tea, coffee and sugar free beverages like diet soda). Participants were prescribed a specific number of items from each food group based on their individual energy requirements (-40%). All participants were taught how to measure food portions by a registered dietitian at the end of our first testing session. Plastic food models and measuring cups were used for the demonstration. Participants were also instructed to keep track of their food intake on a daily basis using

MyFitnessPal ® app (MyFitnessPal, Inc., CA, USA), which has been previously used to track changes in EI and macronutrients consumption [18]. A registered dietitian ensured that participants knew how to properly input and track their food intake using the application at the end of the first testing session. Due to the short duration of the CR, we did not adjust the meal plans during the intervention. Of note, participants met weekly with the registered nutritionist throughout the intervention to optimize protocol adherence.

Resistance-Training Intervention

Participants were either randomized to the HVRT group or the LVRT group, performing 30 sets/major muscle group/week (15 sets/minor muscle group/week) or 12 sets/major muscle group/week (6 sets/minor muscle group/week). According to Remmert et al. [16] classification, major muscle groups (major pectoralis, latissimus dorsi, deltoids, quadriceps and hamstrings) were identified as primary contributors to a given movement while minor muscles (triceps brachii, biceps brachii, rectus abdominalis) were considered as secondary contributors to a given movement. Thus, minor muscle groups received half the direct volume (0.5 set) of major muscle groups but were also targeted indirectly in multijoints movements (for example, triceps brachii was directly targeted in 15 direct sets/week, but also indirectly 30 times/week in movements such as the machine chest press and the barbell overhead press). An upper-lower body split was used in this study, with a frequency of 3 upper-body sessions and 2 lower-body sessions per week. The prescribed HVRT was chosen based on studies suggesting that > 30 sets/muscle group/week can lead to greater hypertrophy than LVRT (16 sets/muscle group/week or less) [12, 20]. Conversely, the prescribed LVRT was based on a recent randomized-controlled trial in which 12 sets/muscle group/week was used as a LVRT [18]. Repetitions per set were held between 10 –12 (65% - 75% 1 RM) for both groups and participants were instructed to consequently adjust their loads to fall within that range.

Concentric muscular failure, defined as the incapacity to perform another repetition with proper form, was not mandatory but allowed. We thus instructed participants to complete their set within 1-2 repetitions in reserve [21]. Participants were also asked to complete their sets in a controlled manner and to rest for 90 seconds between sets and exercises. Details regarding the prescribed exercises can be found in the supplemental material section. For standardization reasons, our RT intervention was mainly limited to plate loaded machines or cables.

As mentioned, participants had to complete 5 RT sessions/week, compiling 12 upper-body sessions and 8 lower-body sessions during the 4-week intervention. Participants were provided with two training logs (one for the upper-body and one for the lower-body) where they had to input their RT parameters for each set performed (load used and number of repetitions performed) and for each training session (5x/week). In case of a non-completed training session, participants were asked to add their non-completed RTV on another day during the same week to ensure that the average prescribed number of set/muscle group/week was reached. Additionally, participants had to complete 2 mandatory RT sessions at the laboratory each week. To ensure that participants were completing their RT routine, a member of our research team was present at the laboratory to supervise them.

Study Measurements

Participants were asked to visit the laboratory at the University of Ottawa on 4 separate occasions. The testing sessions were separated as follows: 1) two pre-intervention testing sessions of about 180 minutes (overall assessment) and 60 minutes (strength tests), held on separate days and 2) two consecutive post-intervention testing sessions of about 60 minutes (strength tests) and 180 minutes (overall assessment). The two pre-intervention testing sessions were separated by a 7-day wash-out period where participants were asked to maintain their regular training and dietary habits. Participants had to come to the laboratory between 7:30-8:30am for the overall assessment testing sessions, after an overnight fast and were asked to refrain from vigorous exercise for at least 24h prior to the tests. Participants also had to come to the laboratory one day prior to the intervention and on the last day of the intervention between 6:30-7:30am for their strength tests.

Experimental Session #1

Previous resistance-training volumes

Prior to their first testing session, participants were asked to prepare a document containing their RT routine. Briefly, participants were asked to record all their RT sessions during the 7 days preceding their first testing session. The document had to include their average frequency of RT sessions/week, the name of the exercises performed, the number of sets performed per exercise, the number of repetitions per set as well as the loads used for every single set. Of note, pre-intervention tonnage could not be determined due to the high prevalence of calisthenic exercises in our sample. This information is presented in Supplemental **Table 1.**

24-hour urine collection

A first 24-hour urine collection was completed at the first experimental session. The 24-hour urine collection was used as a proxy of FFM protein turnover. Briefly, participants were provided with three 3-liter polyethylene urine containers (ThermoFisher Scientific, Canada). On the morning of the collection, BM was measured following a complete overnight fast. Participants were instructed to discard the first urine specimen on the day of the collection, but to include the rest as well as their first urine of the following day. Participants were also asked to note and input in MyFitnessPal (MyFitnessPal, Inc., CA, USA) the food consumed on the day of the collection and to weigh it to the nearest gram possible. A food scale (Trudeau Electronic Scale, Trudeau Corporation 1889 Inc., CA, USA) was provided to the participants and they were shown how to properly use the application and how to weigh ingested foods. During the collection period, participants were instructed to store their urine in their refrigerator and bring it with them to their second pre-intervention testing session. Two 24-hour urine collection were completed over the course of the study (Week 2 and Week 4) using the same procedures. Since most training occurred in the afternoon and at nighttime, we were unable to weigh participants fasted at the laboratory for Week 2 urine collection. Therefore, participants had to weigh themselves at home since no specific day was pre-determined for collection. Participants were instructed to follow the same procedures and had to bring their urine sample to the laboratory at their next scheduled training session.

Anthropometrics & Body Composition

Height (HR-100 Height Rod; Tanita Corporation of America Inc. Arlington Heights, IL) and weight (HR-100; BMB-800AS, Tanita Corporation, Arlington Heights, IL., USA) were measured prior to the body composition test. Fat mass (FM) and FFM were measured by dual energy X-ray absorptiometry DEXA) (General Electric Lunar Corporation version 6.10.019, Madison, USA). Our DEXA scan has a coefficient of variation of 1.8% with a correlation score of 0.99 as determined in 12 healthy subjects. All the measurements occurred in the morning after an overnight fast. Participants were asked to wear light clothing (sweatpants, t-shirt, shorts or leggings) and to remove all jewelry (bracelets, necklaces, rings) prior to all measurements.

Indirect Calorimetry

Resting EE was measured with indirect calorimetry (SensorMedics VMax 29N) using the open-hood ventilated technique as previously described [11]. Briefly, concentrations of CO_2 and O_2 were measured for 30 minutes. The first 5 and last 5 minutes were excluded from our calculations and REE was calculated with the Weir equation from gas exchanges obtained during the remaining 20 minutes. Participants were asked to rest quietly in the supine position on a hospital bed without falling asleep. The test occurred in a quiet room standardized at a temperature of 22ºC. All measurements occurred between 7:30-9:30am after an overnight fast. Ethanol burning tests are routinely performed to control the quality of measurements, as previously described [22, 23]. Our most recent analysis revealed ± 4.2% and 0.39% difference in CO_2 and O_2 measures, respectively.

Experimental Session #2

Urine collection, nitrogen ingestion and nitrogen balance calculations

Upon arrival at the laboratory, the participants were asked to provide their urine sample. Firstly, the urine containers were vigorously shaken, and the total urine volume was measured using a 1-liter graduated cylinder. A 4mL sample was then collected, transferred inside a 12mL borosilicate glass vial and stored at –80 degrees Celsius in an ultra-low temperature freezer (Fisher Scientific, Canada). All samples were analyzed at the Stable Isotope Laboratory at the University of Ottawa. Briefly, 2-3mg of urine were stored in tin capsules, flushed with ultra-pure helium, celled manually and later analyzed using the Dumas method with a CHNS elemental analyzer (varioIsotopecube, Elementar Americas, Inc.). Nitrogen was analyzed automatically and in continuous flow. Miscellaneous and fecal nitrogen losses were estimated at 5mg/kg BM and 2g/day, as previously reported [24, 25]. From the self-reported protein intake assisted by the study dietitian, a dietary nitrogen content was calculated. Finally, nitrogen balance (NBAL) was determined using the following equations, as done previously [24, 25]:

1. Total Nitrogen Intake = total protein consumed / 6.25
2. Total Nitrogen Excretion = ((Nitrogen Content / sampled urine volume) * total urine volume)
3. State of Balance = Total Nitrogen Intake – (Total Nitrogen Excretion + Miscellaneous Losses + Fecal Losses)

Strength Testing

All physical testing occurred between 6:30-8:00am at the laboratory. Participants were asked to not train the day before physical testing. Prior to the strength tests, a 5-minute warm-up was allowed, either on a treadmill or a stationary bike. Participants were asked to maintain a light-to-moderate subjective intensity during their warm-up. Then, the strength tests occurred in the following order: 1) horizontal single-leg leg press, 2) bilateral chest press and 3) bilateral machine row. Participants were asked to perform a specific warm-up on each machine for 3 sets of 10 repetitions using submaximal and self-selected weights. A 1-minute rest was allowed between each warm-up set. Then, participants were asked to complete their 5 RM tests using self-selected weights. A 3-minute rest interval was allowed between each 5 RM set and between each exercise. Three 5 RM trial were allowed per participants. Participants were instructed to exert maximal effort on each 5 RM set. The maximal weight used for a 5 RM set was recorded as previously reported [8]. All strength tests were performed on plate-loaded cable machines.

Statistical Analysis

Sample size calculations were performed with G*Power 3.1. Our estimate of effect size was obtained from the study of Roth et al. [18] that also had 2 treatment groups with varying RTV. Sample size calculations with G*Power 3.1 revealed that 14 participants/group would be needed to achieve a = 0.05 and b = 0.80 with an effect size of 0.23 for the main study outcome (between-group difference in FFM). Statistical analysis included descriptive statistics (expressed as mean and standard deviation). Baseline characteristics were assessed using a two-way ANOVA. Between-groups and within-groups differences in BM, FM, %FM, FFM, RMR and 5 RM strength were assessed using a general two-way repeated measure ANOVA (group x time). Two-way mixed repeated measures ANOVA were used as our statistical model to assess changes in tonnage (group x time), prescribed and reported energy and macronutrient consumption (group x time) and NBAL state (group × time). If the null hypothesis was rejected by the ANOVAs, a Holm-Bonferroni correction was applied to identify the difference between groups. The Alpha level used in this analysis was held at 0.05. Data analysis was completed using JASP 0.17.1.0

Results

Baseline measurements

Baseline BM ($F (1, 14) = 5.859$, $p = 0.03$) and FM ($F (1, 14) = 5.681$, $p = 0.032$) were significantly greater among HVRT (**Table 1**). No group difference was noted for baseline %FM, FFM ($p > 0.05$) NREE, TDEE, mean VO2, mean VCO2 and RER ($p > 0.05$).

Similarly, no baseline group difference was noted for previous frequencies, training experience and most muscle groups ($p > 0.05$), except for baseline triceps brachii, which was higher in HVRT ($F (1, 14) = 5.423$, $p = 0.035$) (**Supplemental Table 1**).

Body composition changes

A significant effect of the intervention was noted for BM (mean post – mean pre ± standard error) (Δ – 4.2 ± 0.50 kg) ($F (1, 14) = 69.314$, $p < 0.001$, $\eta^2 p = 0.832$), in which BM was reduced by Δ – 4.4 ± 2.2kg and Δ - 4.0 ± 1.8kg in HVRT and LVRT, respectively. As shown in **Figure 2**, significant reductions in FM (Δ – 3.7 ± 0.4kg) ($F(1, 14) = 77.055$, $p < 0.001$, $\eta^2p = 0.846$) (Δ – 3.9 ± 1.9kg and Δ – 3.3 ± 1.5kg for HVRT and LVRT, respectively) was observed, but changes were not different between groups (**Figure 2**). As shown in **Figure 2**, no effect of the intervention ($F(1, 14) = 0.519$, $p = 0.483$, $\eta^2p = 0.036$) or group*intervention ($F(1, 14) = 0.090$, $p = 0.768$, $\eta^2p = 0.006$) were noted for FFM. A significant of the intervention was also seen for %FM (Δ – 3.5 ± 0.43%) ($F(1, 14) = 67.050$, $p < 0.001$, $\eta^2p = 0.827$), with no group*intervention effect (results not shown).

Indirect calorimetry

A significant effect of the intervention was observed for REE (Δ – 151 ± 34 kcal) ($F(1, 14) = 19.521$, $p < 0.001$, $\eta^2p = 0.582$), VO2 (Δ – 0.021 ± 0.005 L/min) ($F(1, 14) = 15.909$, $p = 0.001$, $\eta^2p = 0.532$) and VCO2 (Δ – 0.024 ± 0.007 L/min) ($F(1, 14) = 10.863$, $p = 0.005$, $\eta^2p = 0.437$), which were all reduced with no significant group*intervention effects (**Table 2**).

Strength, resistance-training volume and compliance

A significant effect of the intervention was observed for 5 RM chest press (Δ + 9.5 ± 47.8kg) ($F(1, 14) = 14.131$, $p = 0.002$, $\eta^2p = 0.502$), 5 RM machine row (Δ + 9.9 ± 34.1kg) ($F(1, 14) = 23.452$, $p < 0.001$, $\eta^2p = 0.626$), 5 RM left-leg leg press (Δ + 16.4 ± 53.3kg) ($F(1, 14) = 26.293$, $p < 0.001$, $\eta^2p = 0.653$) and 5 RM right-leg leg press (Δ + 15.2 ± 52.9kg) ($F(1, 14) = 14.483$, $p =0.002$, $\eta^2p = 0.508$) (**Table 3)**. Additionally, significant group*intervention interactions were noted for 5 RM chest press ($F(1, 14) = 4.684$, $p = 0.048$, $\eta^2p = 0.251$), 5 RM left-leg leg press ($F(1, 14) = 4.580$, $p = 0.050$, $\eta^2p = 0.246$) and 5 RM right-leg leg press ($F(1, 14) = 6.417$, $p = 0.024$, $\eta^2p = 0.314$). A Holm-Bonferroni post-hoc analysis revealed that significantly greater increases in strength were noted for HVRT for 5 RM chest press ($p = 0.005$, 95% CI [4.0, 26.1]), left-leg leg press ($p < 0.001$, 95% CI [9.4, 37.2]) and 5 RM right-leg leg press ($p = 0.003$, 95% CI [8.0, 42.7]).

Tonnage was calculated from training logs obtained from participants. All training logs were returned for analyses, and each training session was reported to be completed. As designed, significant group*intervention effects were observed for upper-body tonnage ($F(3, 42) = 5.812$, $p = 0.002$, $\eta^2p = 0.293$) and lower-body tonnage ($F(3, 42) = 3.915$, $p = 0.015$, $\eta^2p = 0.219$) $p = 0.015$, $\eta^2p = 0.219$) (**Figure 3**). A group*intervention Holm-Bonferroni post-hoc analysis revealed that HVRT significantly increased for both upper-body ($p = 0.002$, 95% CI [26112, 15997 kg/28 days]) and lower-body ($p = 0.001$, 95% CI [4141, 19563 kg/28 days]) tonnage from Week 1 to Week 4 of the intervention while upper-body ($p = 0.646$, 95% CI [3700, 9685 kg/28 days]) and lower-body ($p = 0.128$, 95% CI [2221, 13201 kg/28 days]) tonnage were not different throughout the intervention in LVRT. Furthermore, between-groups Holm-Bonferroni post-hoc analysis confirmed, as expected, that a significantly higher tonnage was achieved throughout the intervention for HVRT for both upper-body ($p < 0.001$, 95% CI [22151, 52811 kg/28 days]) and lower-body ($p = 0.003$, 95% CI [10774, 43686 kg/28 days]). Compliance to our in-laboratory RT sessions was

80 ± 31% and 91 ± 20% in HVRT and LVRT, respectively. No significant difference in compliance was noted.

Energy intake and macronutrient consumption

As seen in **Figure 4**, significant group*intervention effect for EI was detected ($F (4, 52) = 3.267$, $p = 0.018$, $\eta^2p = 0.201$), indicating that prescribed and reported energy consumption was greater among HVRT. This is explained by baseline TDEE, as HVRT had greater energy needs than LVRT in line with their higher BM. However, no effect was detected at any timepoint following a Holm-Bonferroni correction, suggesting that reported EI was similar in both group across all timepoints. Additionally, a significant group*intervention effect for carbohydrates intake was detected ($F (4, 52) = 5.857$, $p < 0.001$, $\eta^2p = 0.311$), indicating that prescribed and reported carbohydrates were greater among LVRT (**Figure 4**). This is in line with our prescribed macronutrients, as HVRT had higher protein intake (due to their higher baseline BM) while fat intake was relatively similar between groups. However, no effect was detected at any timepoint following a Holm-Bonferroni correction, suggesting that carbohydrate consumption was similar in both group across all timepoints. No effect of the intervention was detected for protein and fat consumption ($p > 0.05$).

From the estimated baseline TDEE, reductions of 1228 ± 208 kcal/day (34 373 ± 5827 kcal/28 days) and 1181 ± 138 kcal/day (33 076 ± 3850 kcal/28 days) were prescribed to achieve a 40% deficit in HVRT and LVRT, respectively. Average reported calorie intake were 1829 ± 290 kcal/day and 1706 ± 180 kcal/day in HVRT and LVRT, respectively, corresponding to estimated deficits of about 40.3 ± 20.0% and 42.2 ± 14.0% in HVRT and LVRT, respectively (**Figure 4**). Based on the observed changes in FM and FFM and on the estimated energy equivalents of FM and FFM [26], daily and total deficits were 1331 ± 625 kcal/day (37 262 ± 17 511 kcal/28 days) and 1144 ± 482 kcal/day (32 034 ± 13 490 kcal/28 days) for HVRT and LVRT, respectively. This corresponds to actual deficits of 44 ± 22% and 39 ± 17% for HVRT and LVRT, respectively. Of note, estimated total energy deficits for the intervention (from the caloric equivalents [26]) were not different between groups ($F (1, 14) = 0.447$, $p = 0.514$, $\eta^2p = 0.031$).

Nitrogen balance

Every participant completed their 24-hour urine collection, with the exception of one participant in HVRT for Week 2. Baseline NBAL was negative for both groups and remained negative throughout the intervention. However, no effect of the intervention ($F (2, 26) = 0.110$, $p = 0.896$, $\eta^2p = 0.009$) or group*intervention ($F (2, 26) = 0.169$, $p = 0.845$, $\eta^2p = 0.013$) was noted for 24-hour NBAL (**Figure 5**). Similarly, removing baseline measurements from our analysis did not alter our results or conclusions ($p > 0.05$).

Discussion

We conducted a 4-week intervention which comprised of a CR and a high-protein diet (2.3g/kg BM) in resistance-trained men and women with varying RTV (30 sets/muscle group/week as a HVRT and 12 sets/muscle group/week as a LVRT). We are amongst the few who have used such high training volume (30 sets/muscle group/week) [12, 14, 16, 20], and to our knowledge the first to do so under CR. Additionally, we are the first group to directly investigate the influence of HVRT and LVRT on NBAL under CR. We hypothesized that 30 sets/muscle group/week would be superior at preventing both FFM losses and strength decrements compared to 12 sets/muscle group/week. According to our results, 12 sets/muscle group/week is sufficient to maintain FFM during a 40% CR while those aiming to increase their strength during CR would appear to substantially benefit from HVRT (30 sets/muscle group/week) under the conditions described in this study.

Body composition

Significant reductions in BM, FM and %FM were observed, while no effect was noted for FFM following the intervention **(Figure 2)**. A recent study reported that a 12 vs. 20 sets/muscle group/week produced similar reductions in FFM during a 6-week intervention employing a 33% CR alongside a high-protein diet (2.8g/kg FFM) [18]. In contrast, FFM remained similar in both our LVRT and HVRT groups in our study (**Figure 2**). Those differences can likely be explained by the duration of the studies, as longer CR have been associated with greater FFM losses [7, 10]. Additionally, our participants showed baseline FM percentage levels ~ 7% greater than those from Roth et al. [18]. Given that higher baseline FM levels may provide a sparing effect on FFM [6], it could be speculated that our participants did not experience significant reductions in FFM levels due to their initial FM levels. Interestingly, our results also differ from those obtained by Longland et al. [1], where a cohort of recreationally active men underwent a 4- week 40% CR with varied protein intakes (2.4g/kg BM or 1.2g/kg BM). By the end of the intervention, non-significant increases in FFM were noted for their low-protein group while their high-protein group observed a significant 1.2kg increase in FFM [1]. Given that untrained individuals possess greater potential for hypertrophy (absence of neuromuscular adaptations necessary for improvements in strength and hypertrophy) [8], it could be that the increases in FFM were in part driven by the new stimuli provided by the intervention. Of note, our groups did not reduce their previous RTV, when analyzed as weekly sets/muscle group. HVRT increased its volume from pre-intervention but was also able to increase its tonnage during the intervention while LVRT maintained their pre-study volume and tonnage during the intervention as shown in **Supplemental - Table 1** and **Figure 3**. Accordingly, a recent review suggested that maintenance and increases of RTV would confer a similar effect on FFM retention under CR while decreases in RTV would be more likely to induce losses of FFM [17]. Therefore, our data suggest that both maintained and increased RTV can maintain FFM under CR, but we cannot exclude that reductions in RTV might prevent that effect.

Strength

Our results suggest that HVRT increases strength to greater extent than LVRT (**Table 3**). We had hypothesized that the maintenance of strength would be associated with greater retention of FFM induced by HVRT. In fact, as much as 35% of strength increases over an 8-week period can be attributed to changes in hypertrophy [27]. However, this was not the case in our study since FFM was maintained somewhat equally in both groups (**Figure 2**). In line with our findings, it was reported that strength was preserved despite significant reductions in fiber cross-sectional area after 32 weeks of detraining in both elderly and young individuals performing 1/3 or 1/9 of their baseline RTV [28]. A clearer dissociation between strength and FFM during CR was shown in recent work by Roth et al. [18], where participants increased their leg press weight (+ 31.7 kg and + 35.6 kg for HVRT and LVRT, respectively) despite observing significant reductions in FFM [18]. Therefore, changes in strength may not solely be attributable to FFM retention. Although speculative, it is possible that strength improvements seen in HVRT may be explained by neuromuscular adaptations from higher exposure/practice on specific lifts throughout the intervention. Indeed, 4 sets/exercise performed for 8-12 repetitions yielded similar increases in strength as 5 sets/exercise performed at 1 RM [29], suggesting that higher exposure (via repetitions, for instance) can yield to similar increases in strength than a strength-oriented routine. In fact, a recent meta-regression found a strong association between strength and training frequency implying more practice yields better strength gains [16]. However, the authors also reported that minimal RTV is required to induce strength gains and that training at higher percentages of 1 RM was the main driver. It is thus possible that strength gains in HVRT may be attributable to other factors since our cohort performed exercises in the 10-12 repetition range. Such changes could be in part attributed to the increased volumes prescribed to HVRT in our study, as seen in **Supplemental - Table 1**. In fact, a 32-set bodybuilding routine yielded greater 1RM squat gain than a 16-set routine in men [12]. Their participants were asked to perform their sets at 75%-85% 1RM, which would suggest that a HVRT-moderate intensity bodybuilding split routine may be a viable option for strength improvements. Furthermore, their 32-set group drastically increased their lower-body RTV, which would suggest that increases in strength may not only be obtained by high-intensities but also through increases in volume loads. Of consideration, we did not directly track training duration, participants estimated training duration at about 45-60 minutes and 90-120 minutes, LVRT and HVRT, respectively. As such, changes in strength observed in HVRT could be the result of either: 1) A greater exposure to the prescribed movements, enhancing neuromuscular adaptations; and/or 2) Through the increase of absolute volume load, although more research is needed to clarify this issue.

Energy expenditure

A significant reduction in REE (~-8%) was detected for the entire sample alongside a decrease in BM (~-5%) and this despite the maintenance of FFM **(Table 2** and **Figure 2**). Additionally, significant reductions of mean VO2 suggest that changes in REE were not driven by a change in substrate use [11]. Interestingly, the practice of RT has been shown, at least in individuals living with overweight (ILWO), to preserve REE through the preservation of FFM [30], whereas RT had no effect on REE in a group of older females [31]. In this study we show that despite the preservation of FFM with RT (LVRT and HVRT) (**Figure 2**), REE was nonetheless significantly reduced.

Limitations

First, our sample size was relatively small (n = 16) compared to previous work of Roth and colleagues (n = 38) [18]. However, changes in FFM were not different between groups ($\eta^2p = 0.006$), which shows the absence of trend in our primary outcome and strongly suggests that adding more participants would have likely not altered the conclusions. Second, NREE was assessed by accelerometry and only activities > 3 METs were included in our calculations. Therefore, we cannot exclude an underestimation of NREE (and thus of daily energy expenditure). However, the estimated deficits based on body composition changes [26] were approximately 44% and 39% for HVRT and LVRT, respectively, suggesting a negligible effect of accelerometry on our calculations of NREE and daily energy expenditure. Third, most participants came from a sporting background and thus mainly engaged in RT routine using free weights. However, most of the prescribed exercises in our intervention were completed on machines, which could have interfered with the true role of RTV on strength development by inducing a beginner effect. Therefore, we do not exclude the possibility that strength increases seen in HVRT were solely due to the incorporation of new movements and/or a new modality of training. Fourth, only two females were recruited in this study due to: 1) Less response compared to men to the recruiting ads and 2) A lack of previous RT experience. We also completed all statistical analyses while excluding female participants. Our results were very similar and did not alter our conclusions. Finally, we do acknowledge that adding CR only group would have improved our study design. However, including a CR only group does present important challenges from a recruitment perspective. First, recruiting experienced resistance-trained individuals in and of itself represents a challenge as they must comply with new dietary and training modalities that may compromise previous FFM gains. Second, it is very likely that most resistance-trained individuals would be hesitant to pause their RT and undertake a CR and risk considerable losses of FFM.

Strengths

Despite all limitations, our study has multiple strengths. First, we are only the second group to investigate the effects of HVRT on body composition and strength under CR. Second, we are the first group that prescribed 30 sets/muscle group/week under CR while being among the few using such RTV in resistance-trained individuals [12, 14, 16, 20]. Third, compliance to our protocol was strong, reaching almost 80% in HVRT and 93% in LVRT. Fourth, the observed changes in BM fall within the average reductions in BM that are induced by daily reductions in energy intake of about 1000kcal/day (**Table 1**) (± 1kg BM/week), which suggests that our tracking was adequate and that our intervention was well tolerated by our participants. Fifth, we used DXA to assess body composition changes, which increases the reliability of our findings. Lastly, our sample was composed of experienced resistance-trained lifters while we concurrently documented their previous routine, which has not been done extensively previously.

Conclusion

We showed that the previous recommendations for hypertrophy under mass-stable conditions (> 10 sets/muscle group/week) are applicable to resistance-trained individuals undergoing CR. Indeed, similar reductions in BM, FM and %FM and REE were noted between groups while FFM was equally maintained in both groups. HVRT resulted significantly greater strength increases than LVRT despite similar changes in FFM. Therefore, athletes and resistance-trained individuals seeking improvements in power-to-mass ratio through increases of strength may appear to benefit from the incorporation of HVRT during periods of CR. Of consideration, the mechanisms underlying such improvements remain to be determined. Future studies should include measurements of neuromuscular activity to clarify how and when such increases occur even when FFM is maintained.

References

1. Longland TM, Oikawa SY, Mitchell CJ, Devries MC, Phillips SM. Higher compared with lower dietary protein during an energy deficit combined with intense exercise promotes greater lean mass gain and fat mass loss: a randomized trial. *Am J Clin Nutr* 2016; **103**(3)**:** 738-46.

2. Mettler S, Mitchell N, Tipton KD. Increased protein intake reduces lean body mass loss during weight loss in athletes. *Med Sci Sports Exerc* 2010; **42**(2)**:** 326-37.

3. Ferguson LM, Rossi KA, Ward E, Jadwin E, Miller TA, Miller WC. Effects of caloric restriction and overnight fasting on cycling endurance performance. *J Strength Cond Res* 2009; **23**(2)**:** 560-70.

4. Pons V, Riera J, Capo X, Martorell M, Sureda A, Tur JA *et al.* Calorie restriction regime enhances physical performance of trained athletes. *J Int Soc Sports Nutr* 2018; **15:** 12.

5. Weinheimer EM, Sands LP, Campbell WW. A systematic review of the separate and combined effects of energy restriction and exercise on fat-free mass in middle-aged and older adults: implications for sarcopenic obesity. *Nutr Rev* 2010; **68**(7)**:** 375-88.

6. Elia M, Stubbs RJ, Henry CJ. Differences in fat, carbohydrate, and protein metabolism between lean and obese subjects undergoing total starvation. *Obes Res* 1999; **7**(6)**:** 597-604.

7. Helms ER, Zinn C, Rowlands DS, Brown SR. A systematic review of dietary protein during caloric restriction in resistance trained lean athletes: a case for higher intakes. *Int J Sport Nutr Exerc Metab* 2014; **24**(2)**:** 127-38.

8. Essentials of strength training and conditioning. . In: *NSCA-National Strength & Conditioning Association (Ed.).* , 2021.

9. Heymsfield SB, Yang S, McCarthy C, Brown JB, Martin CK, Redman LM *et al.* Proportion of caloric restriction-induced weight loss as skeletal muscle. *Obesity (Silver Spring)* 2024; **32**(1)**:** 32-40.

10. Hector AJ, Phillips SM. Protein Recommendations for Weight Loss in Elite Athletes: A Focus on Body Composition and Performance. *Int J Sport Nutr Exerc Metab* 2018; **28**(2)**:** 170-177.

11. Kanaan MF, Nait-Yahia S, Doucet E. The effects of high protein intakes during energy restriction on body composition, energy metabolism and physical performance in recreational athletes. *Eur J Clin Nutr* 2025; **79**(6)**:** 544-552.

12. Brigatto FA, Lima LEM, Germano MD, Aoki MS, Braz TV, Lopes CR. High Resistance-Training Volume Enhances Muscle Thickness in Resistance-Trained Men. *J Strength Cond Res* 2022; **36**(1)**:** 22-30.

13. JBB DEC, Brigatto FA, Zaroni RS, Trindade TB, Germano MD, Junior ACT *et al.* Manipulating Resistance Training Variables to Induce Muscle Strength and Hypertrophy: A Brief Narrative Review. *Int J Exerc Sci* 2022; **15**(4)**:** 910-933.

14. Schoenfeld BJ, Ogborn D, Krieger JW. Dose-response relationship between weekly resistance

training volume and increases in muscle mass: A systematic review and meta-analysis. *J Sports Sci* 2017; **35**(11)**:** 1073-1082.

15. Schoenfeld BJ, Ogborn D, Krieger JW. The dose-response relationship between resistance training volume and muscle hypertrophy: are there really still any doubts? *J Sports Sci* 2017; **35**(20)**:** 1985-1987.

16. Remmert J, Pelland J, Robinson ZH, S.,, Zourdos M. Is There TooMuch of a Good Thing? Meta-Regressions of the Effect of Per-Session Volume on Hypertrophy andStrength. *SportRχiv* 2025**:** 1-31.

17. Roth C, Schoenfeld BJ, Behringer M. Lean mass sparing in resistance-trained athletes during caloric restriction: the role of resistance training volume. *Eur J Appl Physiol* 2022; **122**(5)**:** 1129-1151.

18. Roth C, Schwiete C, Happ K, Rettenmaier L, Schoenfeld BJ, Behringer M. Resistance training volume does not influence lean mass preservation during energy restriction in trained males. *Scand J Med Sci Sports* 2023; **33**(1)**:** 20-35.

19. Calcagno M, Kahleova H, Alwarith J, Burgess NN, Flores RA, Busta ML *et al.* The Thermic Effect of Food: A Review. *J Am Coll Nutr* 2019; **38**(6)**:** 547-551.

20. Schoenfeld BJ, Contreras B, Krieger J, Grgic J, Delcastillo K, Belliard R *et al.* Resistance Training Volume Enhances Muscle Hypertrophy but Not Strength in Trained Men. *Med Sci Sports Exerc* 2019; **51**(1)**:** 94-103.

21. Schoenfeld B, Fisher J, Grgic J, Haun C, Helms E, Phillips S *et al.* Resistance training recommendations to maximize muscle hypertrophy in an athletic population: Position stand of the IUSCA. *International Journal of Strength and Conditioning* 2021; **1**(1)**:** 1-30.

22. Blond E, Maitrepierre C, Normand S, Sothier M, Roth H, Goudable J *et al.* A new indirect calorimeter is accurate and reliable for measuring basal energy expenditure, thermic effect of food and substrate oxidation in obese and healthy subjects. *e-SPEN, the European e-Journal of Clinical Nutrition and Metabolism* 2011; **6:** e-7-e15.

23. Cooper JA, Watras AC, O'Brien MJ, Luke A, Dobratz JR, Earthman CP *et al.* Assessing validity and reliability of resting metabolic rate in six gas analysis systems. *J Am Diet Assoc* 2009; **109**(1)**:** 128-32.

24. Friedlander AL, Braun B, Pollack M, MacDonald JR, Fulco CS, Muza SR *et al.* Three weeks of caloric restriction alters protein metabolism in normal-weight, young men. *Am J Physiol Endocrinol Metab* 2005; **289**(3)**:** E446-55.

25. Pasiakos SM, Cao JJ, Margolis LM, Sauter ER, Whigham LD, McClung JP *et al.* Effects of high-protein diets on fat-free mass and muscle protein synthesis following weight loss: a randomized controlled trial. *FASEB J* 2013; **27**(9)**:** 3837-47.

26. Hall KD. What is the required energy deficit per unit weight loss? *Int J Obes (Lond)* 2008; **32**(3)**:** 573-6.

27. Loenneke JP, Rossow LM, Fahs CA, Thiebaud RS, Grant Mouser J, Bemben MG. Time-course of

muscle growth, and its relationship with muscle strength in both young and older women. *Geriatr Gerontol Int* 2017; **17**(11)**:** 2000-2007.

28. Bickel CS, Cross JM, Bamman MM. Exercise dosing to retain resistance training adaptations in young and older adults. *Med Sci Sports Exerc* 2011; **43**(7)**:** 1177-87.

29. Mattocks KT, Buckner SL, Jessee MB, Dankel SJ, Mouser JG, Loenneke JP. Practicing the Test Produces Strength Equivalent to Higher Volume Training. *Med Sci Sports Exerc* 2017; **49**(9)**:** 1945-1954.

30. Hunter GR, Byrne NM, Sirikul B, Fernandez JR, Zuckerman PA, Darnell BE *et al.* Resistance training conserves fat-free mass and resting energy expenditure following weight loss. *Obesity (Silver Spring)* 2008; **16**(5)**:** 1045-51.

31. St-Onge M, Rabasa-Lhoret R, Strychar I, Faraj M, Doucet E, Lavoie JM. Impact of energy restriction with or without resistance training on energy metabolism in overweight and obese postmenopausal women: a Montreal Ottawa New Emerging Team group study. *Menopause* 2013; **20**(2)**:** 194-201.

Figure legends

Figure 1. Schematic representation of our study design.

Figure 2. Changes in FM and FFM for each participant in the LVRT and HVRT groups from pre- to post-intervention. A Significant decrease in FM was observed for both groups ($p < 0.001$). B No significant change in FFM was observed from pre-to post-intervention in either group.

Figure 3. Upper- and lower-body total tonnage during the intervention in HVRT and LVRT. **A** Significant increase in upper-body tonnage was noted for HVRT (*$p = 0.002$) while it remained similar in LVRT. HVRT upper-body tonnage was significantly greater than LVRT throughout the intervention (‡ $p < 0.001$). **B** Significant increase in lower-body tonnage was noted for HVRT (*$p = 0.001$) while it remained similar in LVRT. HVRT lower-body tonnage was significantly greater than LVRT throughout the intervention (‡ $p = 0.003$).

Figure 4. Prescribed and reported energy, protein, fat and carbohydrate intake in HVRT and LVRT. **A and B** Significant group by time effects for prescribed and reported kilocalories *(*$p < 0.05$)*)* and carbohydrates *(*$p < 0.001$*)* were noted. However, no difference in prescribed and reported kilocalories and carbohydrates was detected following a Holm-Bonferroni correction. **C and D** No effect of the intervention was noted for prescribed and reported protein and fat.

Figure 5. 24-hour total nitrogen balance both before and during the intervention in HVRT and LVRT.

Table 1. Baseline characteristics in HVRT and LVRT [1].

	HVRT	LVRT	Group (p values)
Age (years)	22.6 ± 2.6	25.1 ± 4.4	0.193
Height (cm)	177.6 ± 4.9	175.4 ± 6.5	0.448
Non-REE (kcal/day)	699 ± 402	786 ± 218	0.596
Total daily EE (kcal/day)	3062 ± 512	2953 ± 344	0.626
Body-mass (kg)	91.7 ± 10.7	80.5± 7.6	0.030
Fat-free mass (kg)	66.1 ± 8.7	61.6 ± 6.5	0.262
Fat mass (kg)	25.6 ± 6.6	19.0 ± 4.3	0.032
Percentage fat mass (%)	28.9 ± 6.6	24.4 ± 5.1	0.152

Values are expressed in means and standard deviations. EE = Energy Expenditure; REE = Resting Energy Expenditure [1.] Total sample (*n* = 16) was composed of *n* = 7 men and *n* = 1 women per group.

Table 2. Changes in indirect calorimetry from pre- to post-intervention across HVRT and LVRT [1].

	Pre		Post		P Values	
					Group	Inter
	HVRT	LVRT	HVRT	LVRT		
REE (kcal/day)	2085 ± 271	1898 ± 123	1970 ± 279	1712 ± 120	0.044	0.00
Mean VO_2 (l/min)	0.304 ± 0.040	0.280 ± 0.017	0.291 ± 0.042	0.250 ± 0.019	0.039	0.00
Mean VCO_2 (l/min)	0.240 ± 0.035	0.210 ± 0.018	0.208 ± 0.035	0.198 ± 0.016	0.032	0.00

Values are expressed in means and standard deviations. REE = Resting Energy Expenditure.

[1.] Total sample (*n* = 16) was composed of *n* = 7 men and *n* = 1 woman per group.

Table 3. Changes in 5 RM strength from pre- to post-intervention for HVRT and LVRT [1].

	Pre		Post		ΔChanges (%)		P values
							Group
	HVRT	LVRT	HVRT	LVRT	HVRT	LVRT	
5 RM chest press (kg)	80.7 ± 31.3	85.6 ± 36.6	95.7 ± 36.2	89.6 ± 35.0	18.1 ± 13.7	6.6 ± 12.0	0.972
5 RM machine row (kg)	91.9 ± 25.9	84.2 ± 18.0	105.8 ± 30.3	90.1 ± 20.1	15.0 ± 8.0	7.2 ± 10.2	0.340
5 RM right-leg leg press (kg)	87.6 ± 36.8	81.2 ± 32.1	112.9 ± 50.1	86.2 ± 26.0	27.0 ± 23.8	9.8 ± 14.0	0.380
5 RM left-leg leg press (kg)	88.7 ± 39.0	75.0 ± 27.9	112.0 ± 49.5	84.5 ± 28.3	25.3 ± 21.3	14.0 ± 12.0	0.281

Values are expressed in means and standard deviations.

[1.] Whole sample (n = 16) was composed of n = 7 men and n = 1 woman per group.

Supplemental Table 1. Baseline resistance-training experience and parameters in HVRT and LVRT [1].

	HVRT	LVRT	Group (p values)
Resistance-training experience (yrs)	5.0 ± 3.8	4.7 ± 3.5	0.882
Past resistance-training (session/wk)	4.3 ± 0.9	4.3 ± 0.9	1.000
Pre-study pectoralis weekly sets	18.0 ± 4.2	17.3 ± 6.6	0.79
Pre-study rowing/pulling weekly sets	16.9 ± 8.0	16.5 ± 8.1	0.927
Pre-study deltoids weekly sets	18.3 ± 7.4	14.9 ± 8.1	0.398
Pre-study bicep brachialis weekly sets	14.1 ± 6.8	9.9 ± 3.7	0.144
Pre-study triceps brachialis weekly sets	15.9 ± 4.9	9.9 ± 5.4	0.035
Pre-study quadricep weekly sets	13.4 ± 5.1	11.3 ± 5.1	0.419
Pre-study hamstring weekly sets	8.6 ± 4.5	9.1 ± 3.2	0.802
Pre-study abdominal weekly sets	7.6 ± 4.6	10.1 ± 4.5	0.289

Values are expressed in means and standard deviations.

[1.] Total sample (*n* = 16) was composed of *n* = 7 men and *n* = 1 woman per group.

Figure 1.

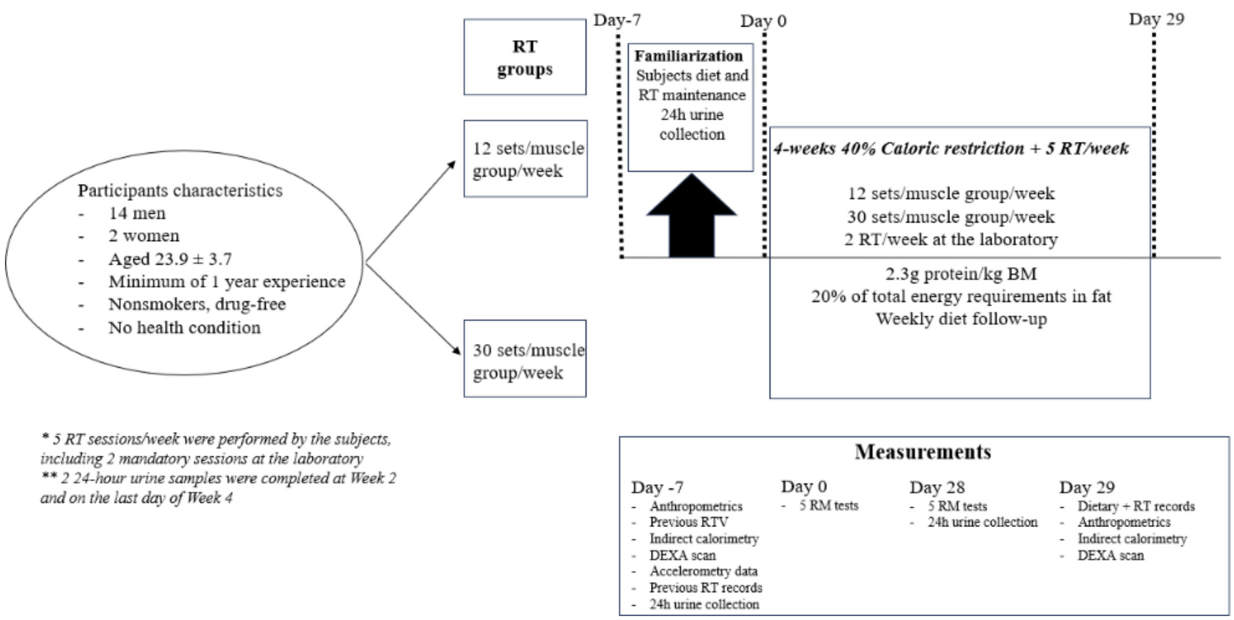

Day-7
Day 0
Day 29
RT groups
Familiarization
Subjects diet and RT maintenance
24h urine collection
12 sets/muscle group/week
30 sets/muscle group/week
Participants characteristics
- 14 men
- 2 women
- Aged 23.9 ± 3.7
- Minimum of 1 year experience
- Nonsmokers, drug-free
- No health condition
4-weeks 40% Caloric restriction + 5 RT/week
12 sets/muscle group/week
30 sets/muscle group/week
2 RT/week at the laboratory
2.3g protein/kg BM
20% of total energy requirements in fat
Weekly diet follow-up
* 5 RT sessions/week were performed by the subjects, including 2 mandatory sessions at the laboratory
** 2 24-hour urine samples were completed at Week 2 and on the last day of Week 4
Measurements
Day -7
- Anthropometrics
- Previous RTV
- Indirect calorimetry
- DEXA scan
- Accelerometry data
- Previous RT records
- 24h urine collection
Day 0
- 5 RM tests
Day 28
- 5 RM tests
- 24h urine collection
Day 29
- Dietary + RT records
- Anthropometrics
- Indirect calorimetry
- DEXA scan

Figure 2.

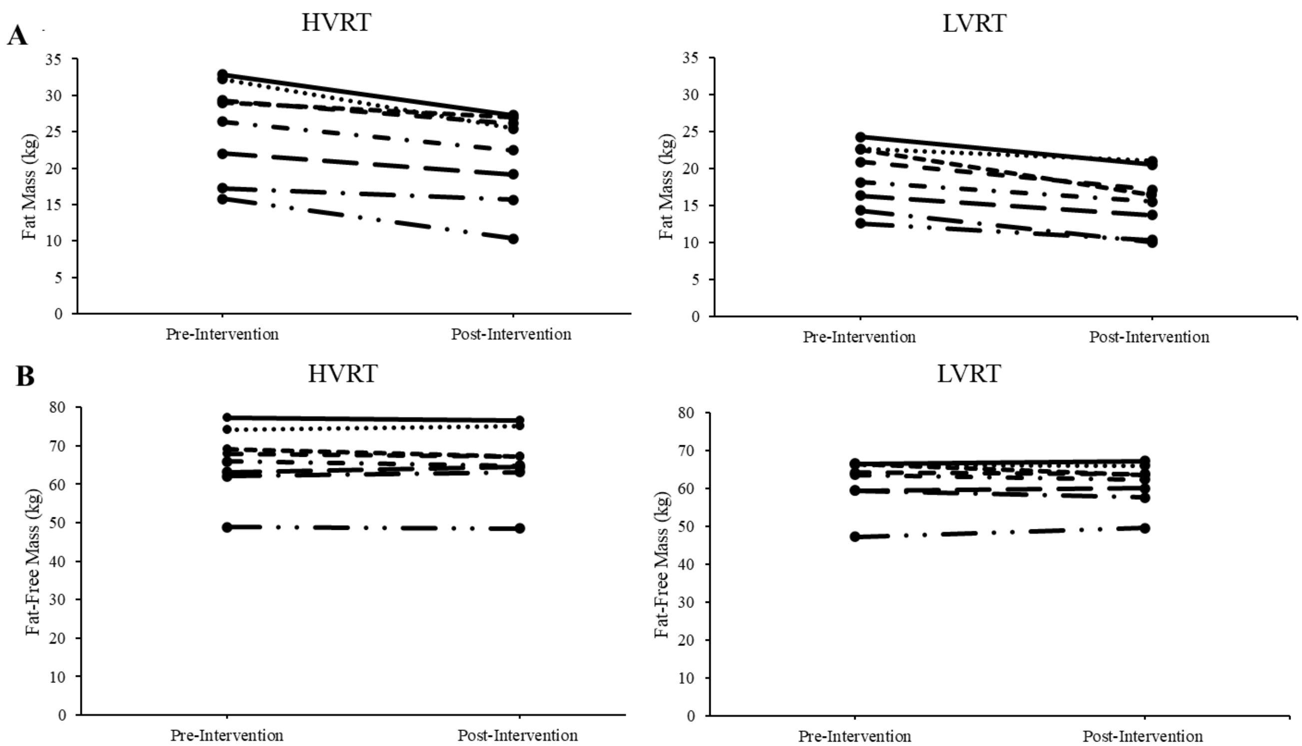

A
HVRT
LVRT
Fat Mass (kg)
35
30
25
20
15
10
5
0
Pre-Intervention
Post-Intervention
B
Fat-Free Mass (kg)
80
70
60
50
40
30
20
10
0

Figure 3.

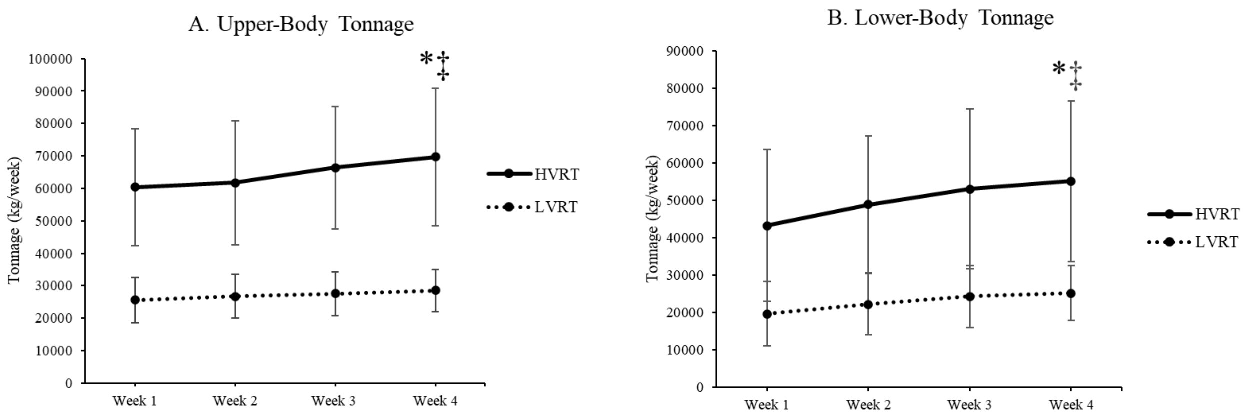


Figure 4.

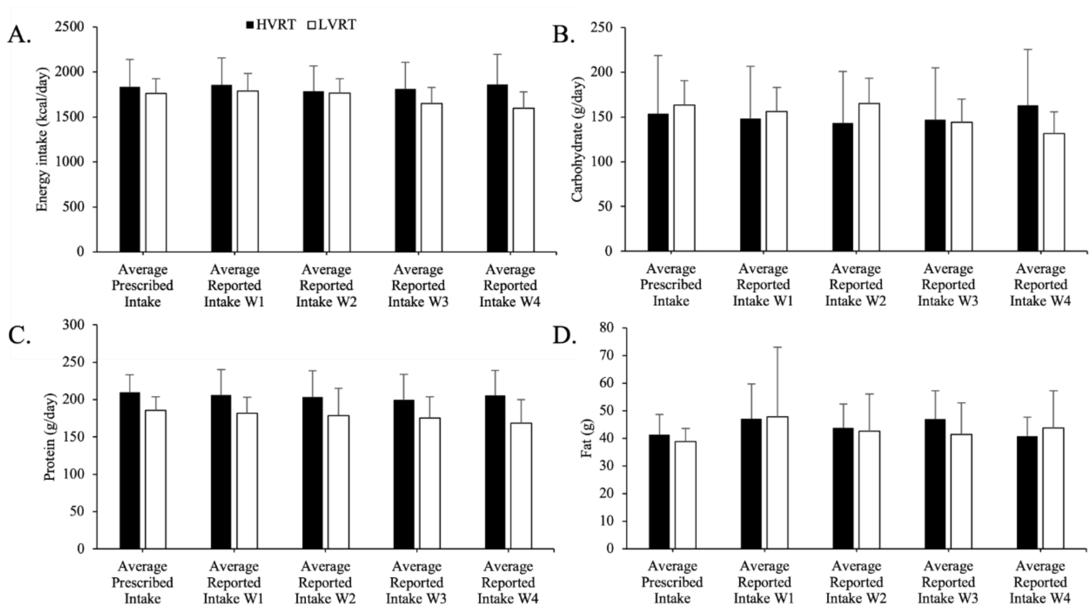
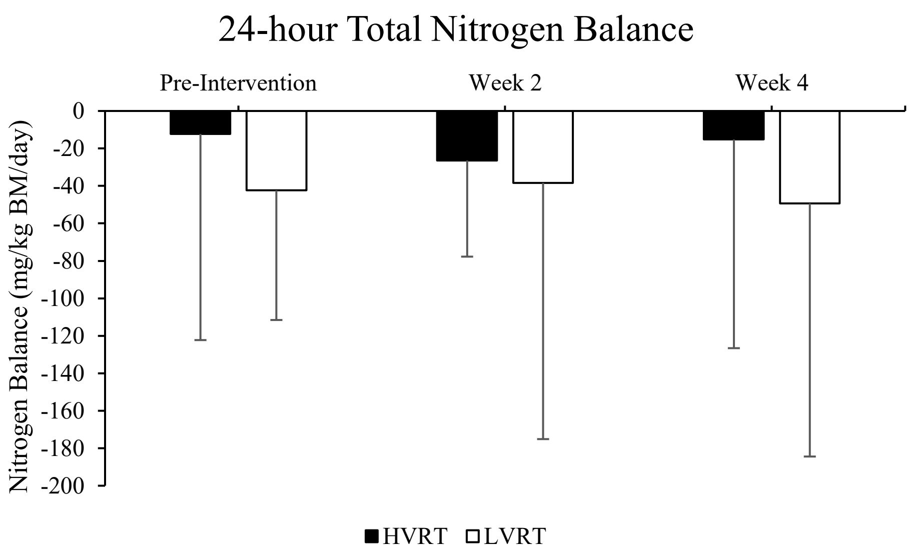


Figure 5.


24-hour Total Nitrogen Balance
Pre-Intervention
Week 2
Week 4
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
Nitrogen Balance (mg/kg BM/day)
HVRT
LVRT

DATA AVAILABILITY

The collected and analyzed datasets of the current study are not publicly available. De-identified and processed data can be requested from the corresponding author for academic purposes after completing a signed data access form. Only de-identified data can be provided to protect participant privacy.

ACKNOWLEDGEMENTS

We thank all participants for taking part in our study.

AUTHOR CONTRIBUTION

SNY and *ÉD*: conceptualization, methodology, data analysis, writing – original draft. *SNY, ÉD* and *MFK*: writing - review & editing. *SNY* and *ÉD*: design of exercise program. *SNY, MFK, NB and AD*: data collection and analysis. *ÉD and SNY*: supervision, project administration. *All authors* read and approved the final version of the manuscript and accepted responsibility for the decision to submit for publication.

FUNDING

This study received no specific funding.

COMPETING INTEREST

No conflict of interest to declare.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

The ethics committee of the University of Ottawa (H-01-24-9926 - REG-9926) approved the study protocol. All participants provided their written consent to participate. This study conformed to the principles of the Declaration of Helsinki.

Chapter 4: General Discussion

In this study, we demonstrated that the incorporation of 30 sets/muscle group/week alongside high protein intake (2.3g/kg BM) during a 40% CR did not provide significant advantages for FFM maintenance, REE maintenance and 24-hour NBAL state compared to 12 sets/muscle group/week. Interestingly, we found that HVRT resulted in greater strength increase than LVRT. We acknowledge that these findings are limited by the design of the present study and by several factors that may have influenced the outcomes observed. Some of these factors are related to: 1) caloric restriction (restriction length, magnitude of the deficit and compliance); 2) nutrition (protein quality, quantity and frequency of protein consumption throughout the day); 3) resistance training (parameters, modality of the exercises, type of strength testing) and; 4) methods used to assess body composition (indirect measures of hypertrophy). Some considerations are given to each of these factors in the following sections.

Caloric Restriction

CR is used in both ILWOs and athletes, and FFM losses are common even with RT (Weinheimer *et al*., 2010). We showed similar losses in BM between HVRT and LVRT, yet losses were highly variable (HVRT: −6.3 to −0.8 kg; LVRT: −6.5 to −1.6 kg). Mean losses (-4.4kg and –4.0kg in HVRT and LVRT, respectively) implied ~40% versus ~33% deficits, highlighting that CR-induced reductions in BM involve physiological (decreases in REE and/or non-exercise adaptative thermogenesis) (von Loeffelholz *et* Birkenfeld, 2022), behavioral (adherence and under-logging) and methodological (free-living sleep and stress) changes. For example, HVRT may raise total daily energy expenditure (TDEE) but also cause fatigue and reduce involuntary physical activity. Similarly, rare are studies adjusting kilocaloric intake based on changes in REE and physical activity energy expenditure during CR. Therefore, including weekly REE and daily steps/non-exercise adaptative thermogenesis measurements would allow for better adjustments of EI. On the other hand, providing meals and asking participants to stay at the laboratory during the intervention could reduce variability linked to diet. Finally, monitoring sleep and perceived stress may also help understand how appetite variations affect variability among the sample (Darku *et* Diyaolu, 2025).

Protein Intake

Our nutritional intervention was based on data suggesting that a high-protein – moderate-carbohydrate – low-fat diet could reduce FFM losses (Helms *et al*., 2015 ; Helms *et al*., 2014 ; Hsu *et al*., 2023). Therefore, we decided to prescribe 2.3g/kg BM protein intake to try to mitigate FFM losses during our 4-week 40% CR. Protein quality matters; an insufficient amount of essential amino acids – especially leucine – blunts MPS and hypertrophy (Atherton *et* Smith, 2012 ; Brook, 2025). On the other hand, whey generally induces larger acute MPS than a plant-based bolus (soy, for example) (Damaghi *et al*., 2022), unless the plant-based diet is carefully designed to account for the lack of essential amino acids. The "muscle-full" effect suggests a ceiling effect on MPS with protein intake > 0.4-0.5g/kg BM/meal, which led to the suggestion of consuming > 3 meals/day (Atherton *et* Smith, 2012 ; Brook, 2025 ; Layman, 2024 ; Yasuda *et al*., 2020). Also, the consumption of protein following RT (120-180 min post-training) seems to further enhance MPS and may consequently produce greater hypertrophy (Schoenfeld *et* Aragon, 2018). Of note, we did not standardize protein source nor timing; our results should be interpreted accordingly. We nonetheless encourage future studies to compare a protein-matched plant-based diet versus an omnivorous diet under CR regarding both hypertrophy and strength performances. Similarly, it has recently been proposed that total protein intake rather than timing was a better predictor of hypertrophy (Lak *et al*., 2024). Therefore, we finally propose that future research also compare protein-matched diets, but with a different number of meals and/or different timing.

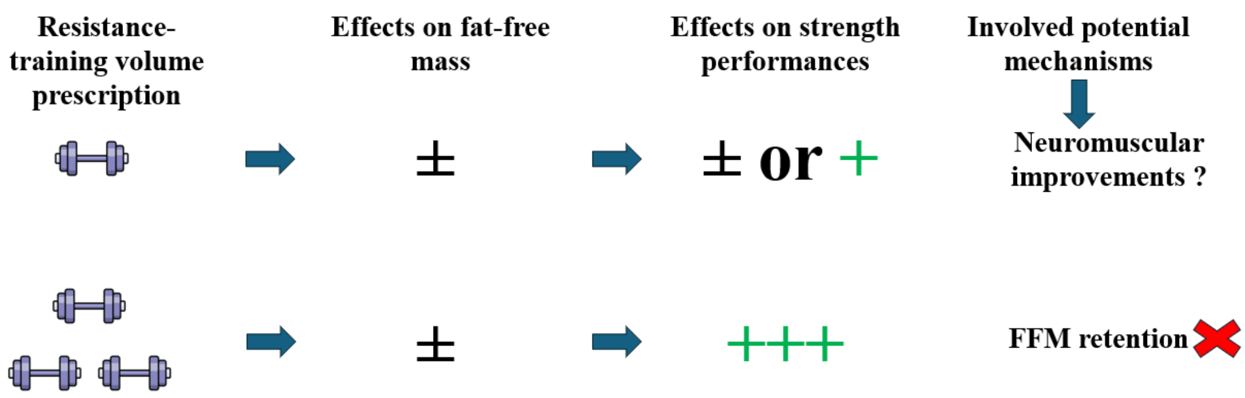
Resistance Training

To preserve internal validity, our RT protocol was fixed (constant rest times, constant repetition range, etc.), but this limited individualization and realism. In clinical settings, RT is periodized and involves a systematic variation in RTV, intensity, exercise selection and rest times to target hypertrophy and/or strength. Many sports employ power-oriented RT (plyometrics, low-load/high-velocity training). However, these contexts differ from powerlifting/bodybuilding in goals and likely hypertrophic potential. Indeed, plyometrics alone may induce hypertrophy but remain less effective than traditional routines in trained individuals (Arntz *et al*., 2022). What is more, it remains unclear whether CR affects strength and power differently. We demonstrated a nonsignificant decrease in broad jump after a 12% deficit despite BM reductions and gains in FFM, as well as 5 RM strength (Kanaan *et al*., 2025), suggesting that velocity-dependent qualities may be more sensitive to CR than strength. In this study, HVRT observed a 5-fold increase in strength over LVRT with similar retention in FFM – consistent with neural adaptations occurring despite no subsequent hypertrophy. To conclude, we propose that future research: 1) Systematically vary repetition-load schemes and rest times depending on the exercises (pluri-articular versus single-joint) and the muscle masses involved, 2) Include different modalities of RT (free weights, machines, cables, bodyweight exercises), 3) Include a wider range of tests, evaluating changes in both strength (1 RM or 5 RM) and power (vertical and/or broad jump), as well as their applicability to a sport-specific context (Special Judo Fitness test in judokas, for example), 4) Incorporate neuromuscular markers to clarify how CR influences force-velocity characteristics.

Body Composition

We intended to use a 4-compartment model (DXA + deuterium oxide dilution for total-body water), but issues with deuterium oxide assays prevented us from using the data. We therefore relied on DXA, a gold-standard 3-compartment model that distinguishes lean tissue, bone and FM. DXA assumes a constant FFM hydration (~ 73.2%), which may change during CR due to fluid redistribution, glycogen depletion and electrolyte changes (Crintea *et al*., 2025), factors that may affect FFM estimates without reflecting true changes in muscle tissue. Furthermore, FFM not only includes skeletal muscle mass, but also organ tissue, connective tissue, and bone mineral content, all of which may respond differently to CR and RT (Haun *et al*., 2019 ; Heymsfield *et al*., 2010). Our design may also create bias in FFM estimates, as HVRT can transiently increase FFM through edema. Such bias may be exacerbated if scans are performed less than 48 hours following RT. Considering this, we propose that future studies incorporate multiple body composition assessments (DXA, bioelectrical impedance, hydrodensiometry), direct measures of hypertrophy (ultrasound or magnetic resonance imagery) and isotope-based total-body water measurements (deuterium oxide dilution) to provide a more comprehensive understanding of FFM changes quality, and separate the testing session from the intervention by a standardized period of at least 48 hours.

Figure 1. A review of the effects of two different RTV prescriptions (30 sets/muscle group/week and 12 sets/muscle group/week) on fat-free mass and strength, and the potential underlying mechanisms of strength improvements.



Note. = 12 sets/muscle group/week, = 30 sets/muscle group/week, ± = no change, + = slight benefit, +++ = great benefit, ? = needs further investigation, x = unlikely

General Conclusions

The main purpose of this thesis was to provide insights on the influence of HVRT and LVRT on FFM and strength performances after a period of CR in resistance-trained individuals. As reviewed in **Figure 1**, it appears that 30 sets/muscle/week produces greater strength adaptations under CR than 12 sets/muscle group/week despite similar body composition changes. We initially thought that greater maintenance of strength performances would be attributed to greater maintenance of FFM, yet FFM was maintained similarly in both groups. Thus, FFM appears to be likely modulated by the deficit itself rather than RTV, while strength increases seem to be mediated by neurophysiological adaptations. Of consideration, our results should be analyzed cautiously, according to our interventions' limitations, as stated in the *General Discussion*. We nonetheless encourage future research to try mimicking real-life settings with their RT interventions while incorporating tests that are specific to the disciplines practised by the participants. Finally, a broader battery of tests (body composition, "direct" measurements of hypertrophy, strength and power tests, etc.) may help provide quality to the changes in FFM as well as to the changes in strength, while providing insights relative to the transferability of such changes to the discipline practised by one.

References

Androulakis Korakakis, P., Wolf, M., Coleman, M., Burke, R., Piñero, A., Nippard, J., & Schoenfeld, B. J. (2024). Optimizing resistance training technique to maximize muscle hypertrophy: A narrative review. *Journal of Functional Morphology and Kinesiology*, *9*(1), 9. https://doi.org/10.3390/jfmk9010009

Areta, J. L., Burke, L. M., Camera, D. M., West, D. W., Crawshay, S., Moore, D. R., ... & Coffey, V. G. (2014). Reduced resting skeletal muscle protein synthesis is rescued by resistance exercise and protein ingestion following short-term energy deficit. *American Journal of Physiology-Endocrinology and Metabolism*. https://doi.org/10.1152/ajpendo.00590.2013

Arntz, F., Mkaouer, B., Markov, A., Schoenfeld, B. J., Moran, J., Ramirez-Campillo, R., ... & Chaabene, H. (2022). Effect of plyometric jump training on skeletal muscle hypertrophy in healthy individuals: a systematic review with multilevel meta-analysis. *Frontiers in physiology*, *13*, 888464. https://doi.org/10.3389/fphys.2022.888464

Atherton, P. J., & Smith, K. (2012). Muscle protein synthesis in response to nutrition and exercise. *The Journal of physiology*, *590*(5), 1049-1057. https://doi.org/10.1113/ hysiol.2011.225003

Baechle, T. R., & Earle, R. W. (Eds.). (2008). *Essentials of strength training and conditioning*. Human kinetics.

Baz-Valle, E., Fontes-Villalba, M., & Santos-Concejero, J. (2021). Total number of sets as a training volume quantification method for muscle hypertrophy: a systematic review. *The Journal of Strength & Conditioning Research*, *35*(3), 870-878. *DOI:* 10.1519/JSC.0000000000002776

Berger, R. (1962). Effect of varied weight training programs on strength. *Research Quarterly. American Association for Health, Physical Education and Recreation*, *33*(2), 168-181. https://doi.org/10.1080/10671188.1962.10613188

Berger, R. A. (1973). Effects of strength improvement on accuracy in a gross motor task. *American corrective therapy journal*, *27*(2), 57-58. PMID: 4707127

Bila, W. C., de Freitas, A. E., Galdino, A. S., Ferriolli, E., Pfrimer, K., & Lamounier, J. A. (2016). Deuterium oxide dilution and body composition in overweight and obese schoolchildren aged 6-9 years. Jornal de Pediatria (Versão em Português), 92(1), 46-52. https://doi.org/10.1016/j.jpedp.2015.08.005

Bilsborough, J. C., Greenway, K., Opar, D., Livingstone, S., Cordy, J., & Coutts, A. J. (2014). The accuracy and precision of DXA for assessing body composition in team sport athletes. *Journal of sports sciences*, *32*(19), 1821-1828. https://doi.org/10.1080/02640414.2014.926380

Brigatto, F. A., Lima, L. E. D. M., Germano, M. D., Aoki, M. S., Braz, T. V., & Lopes, C. R. (2022). High resistance-training volume enhances muscle thickness in resistance-trained men. *Journal of strength and conditioning research*, *36*(1), 22-30. https://doi.org/10.1519/JSC.0000000000003413

Brook, M. S. (2025). Investigating muscle protein synthesis using deuterium oxide: The impact of dietary protein interventions across the lifespan. *Experimental Physiology*. https://doi.org/10.1113/EP092016

Buckner, S. L., Moreno, E. N., & Baxter, H. T. (2023). The dose-response relationship between resistance training volume and muscle hypertrophy: There are still doubts. *Journal of Trainology*, *12*(2), 29-36. https://doi.org/10.17338/trainology.12.2_29

Burd, N. A., Holwerda, A. M., Selby, K. C., West, D. W., Staples, A. W., Cain, N. E., ... & Phillips, S. M. (2010). Resistance exercise volume affects myofibrillar protein synthesis and anabolic signalling molecule phosphorylation in young men. *The Journal of physiology*, *588*(16), 3119-3130. https://doi.org/10.1113/jphysiol.2010.192856

Carrasco, D. I., Delp, M. D., & Ray, C. A. (1999). Effect of concentric and eccentric muscle actions on muscle sympathetic nerve activity. *Journal of Applied Physiology*, *86*(2), 558-563. https://doi.org/10.1152/jappl.1999.86.2.558

Damaghi, M. P., Mirzababaei, A., Moradi, S., Daneshzad, E., Tavakoli, A., Clark, C. C., & Mirzaei, K. (2022). Comparison of the effect of soya protein and whey protein on body composition: a meta-analysis of randomised clinical trials. *British Journal of Nutrition*, *127*(6), 885-895. doi:10.1017/S0007114521001550

Damas, F., Phillips, S. M., Libardi, C. A., Vechin, F. C., Lixandrão, M. E., Jannig, P. R., ... & Ugrinowitsch, C. (2016). Resistance training-induced changes in integrated myofibrillar protein synthesis are related to hypertrophy only after attenuation of muscle damage. *The Journal of physiology*, *594*(18), 5209-5222. https://doi.org/10.1113/JP272472

Damas, F., Phillips, S., Vechin, F. C., & Ugrinowitsch, C. (2015). A review of resistance training-induced changes in skeletal muscle protein synthesis and their contribution to hypertrophy. *Sports medicine*, *45*, 801-807. https://doi.org/10.1007/s40279-015-0320-0

Darku, E. D., & Diyaolu, C. O. (2025). The role of stress, sleep, and mental health in obesity and weight gain. *Int. Res. J. Mod. Educ. Technol. Soc*, *6*, 3216-3235. https://www.doi.org/10.56726/IRJMETS62817

DeLorme, T. L. (1945). Restoration of muscle power by heavy-resistance exercises. *JBJS*, *27*(4), 645-667.

de Camargo, J. B. B., Brigatto, F. A., Zaroni, R. S., Trindade, T. B., Germano, M. D., Júnior, A. C. T., ... & Lopes, C. R. (2022). Manipulating resistance training variables to induce muscle strength and hypertrophy: a brief narrative review. *International journal of exercise science*, *15*(4), 910. doi: 10.70252/VYUB3717

de Moraes, W. M., de Almeida, F. N., Dos Santos, L. E., Cavalcante, K. D., Santos, H. O., Navalta, J. W., & Prestes, J. (2019). Carbohydrate loading practice in bodybuilders: Effects on muscle thickness, photo silhouette scores, mood states and gastrointestinal symptoms. *Journal of sports science & medicine*, *18*(4), 772. PMID: 31827362

Drinkwater EJ, Lawton TW, Lindsell RP, et al. Training leading to repetition failure enhances bench press strength gains in elite junior athletes. J Strength Cond Res 19: 382–388, 2005.

Drummond, M. J., Dreyer, H. C., Fry, C. S., Glynn, E. L., & Rasmussen, B. B. (2009). Nutritional and contractile regulation of human skeletal muscle protein synthesis and mTORC1 signaling. *Journal of applied physiology*, *106*(4), 1374-1384. https://doi.org/10.1152/japplphysiol.91397.2008

Elia, M. R. J. S., Stubbs, R. J., & Henry, C. J. K. (1999). Differences in fat, carbohydrate, and protein metabolism between lean and obese subjects undergoing total starvation. *Obesity research*, *7*(6), 597-604. https://doi.org/10.1002/j.1550-8528.1999.tb00720.x

Farinatti, P., Neto, A. G. C., & Amorim, P. R. (2016). Oxygen consumption and substrate utilization during and after resistance exercises performed with different muscle mass. *International journal of exercise science*, *9*(1), 77. PMID: 27293507; PMCID: PMC4882463.

Ferguson, L. M., Rossi, K. A., Ward, E., Jadwin, E., Miller, T. A., & Miller, W. C. (2009). Effects of caloric restriction and overnight fasting on cycling endurance performance. *The Journal of Strength & Conditioning Research*, *23*(2), 560-570. *DOI:* 10.1519/JSC.0b013e31818f058b

Fink, J., Schoenfeld, B. J., & Nakazato, K. (2018). The role of hormones in muscle hypertrophy. *The Physician and sportsmedicine*, *46*(1), 129-134. https://doi.org/10.1080/00913847.2018.1406778

Friedlander, A. L., Braun, B., Pollack, M., MacDonald, J. R., Fulco, C. S., Muza, S. R., ... & Cymerman, A. (2005). Three weeks of caloric restriction alters protein metabolism in normal-weight, young men. *American Journal of Physiology-Endocrinology and Metabolism*, *289*(3), E446-E455. https://doi.org/10.1152/ajpendo.00001.2005

Garthe, I., Raastad, T., Refsnes, P. E., Koivisto, A., & Sundgot-Borgen, J. (2011). Effect of two different weight-loss rates on body composition and strength and power-related performance in elite athletes. *International journal of sport nutrition and exercise metabolism*, *21*(2), 97-104. https://doi.org/10.1123/ijsnem.21.2.97

Goodman, C. A., Frey, J. W., Mabrey, D. M., Jacobs, B. L., Lincoln, H. C., You, J. S., & Hornberger, T. A. (2011). The role of skeletal muscle mTOR in the regulation of mechanical load-induced growth. *The Journal of physiology*, *589*(22), 5485-5501. https://doi.org/10.1113/jphysiol.2011.218255

Greiwe, J. S., Hickner, R. C., Hansen, P. A., Racette, S. B., Chen, M. M., & Holloszy, J. O. (1999). Effects of endurance exercise training on muscle glycogen accumulation in humans. *Journal of Applied Physiology*, *87*(1), 222-226. https://doi.org/10.1152/jappl.1999.87.1.222

Grgic, J., Mcllvenna, L. C., Fyfe, J. J., Sabol, F., Bishop, D. J., Schoenfeld, B. J., & Pedisic, Z. (2019). Does Aerobic Training Promote the Same Skeletal Muscle Hypertrophy as Resistance Training? A Systematic Review and Meta-Analysis. Sports Medicine, 49(2), 233–254. https://doi.org/10.1007/s40279-018-1008-z

Grgic, J., Schoenfeld, B. J., Orazem, J., & Sabol, F. (2022). Effects of resistance training performed to repetition failure or non-failure on muscular strength and hypertrophy: A systematic review and meta-analysis. *Journal of sport and health science*, *11*(2), 202-211. https://doi.org/10.1016/j.jshs.2021.01.007

Haman, F., Péronnet, F., Kenny, G. P., Doucet, E., Massicotte, D., Lavoie, C., & Weber, J. M. (2004). Effects of carbohydrate availability on sustained shivering I. Oxidation of plasma glucose, muscle glycogen, and proteins. *Journal of Applied Physiology*, *96*(1), 32-40. https://doi.org/10.1152/japplphysiol.00427.2003

Hasegawa, J., Tokuda, E., Yao, Y., Sasaki, T., Inoki, K., & Weisman, L. S. (2022). PP2A-dependent TFEB activation is blocked by PIKfyve-induced mTORC1 activity. *Molecular biology of the cell*, *33*(3), ar26. https://doi.org/10.1091/mbc.E21-06-0309

Haun, C. T., Vann, C. G., Roberts, B. M., Vigotsky, A. D., Schoenfeld, B. J., & Roberts, M. D. (2019). A critical evaluation of the biological construct skeletal muscle hypertrophy: size matters but so does the measurement. *Frontiers in physiology*, *10*, 437252. https://doi.org/10.3389/fphys.2019.00247

Haun, C. T., Vann, C. G., Osburn, S. C., Mumford, P. W., Roberson, P. A., Romero, M. A., ... & Roberts, M. D. (2019). Muscle fiber hypertrophy in response to 6 weeks of high-volume resistance training in trained young men is largely attributed to sarcoplasmic hypertrophy. *PloS one*, *14*(6), e0215267. https://doi.org/10.1371/journal.pone.0215267

Hector, A. J., & Phillips, S. M. (2018). Protein recommendations for weight loss in elite athletes: A focus on body composition and performance. *International journal of sport nutrition and exercise metabolism*, *28*(2), 170-177. https://doi.org/10.1123/ijsnem.2017-0273

Helms, E. R., Zinn, C., Rowlands, D. S., & Brown, S. R. (2014). A systematic review of dietary protein during caloric restriction in resistance trained lean athletes: a case for higher intakes. *International journal of sport nutrition and exercise metabolism*, *24*(2), 127-138. https://doi.org/10.1123/ijsnem.2013-0054

Helms, E. R., Zinn, C., Rowlands, D. S., Naidoo, R., & Cronin, J. (2015). High-Protein, Low-Fat, Short-Term Diet Results in Less Stress and Fatigue Than Moderate-Protein, Moderate-Fat Diet During Weight Loss in Male Weightlifters: A Pilot Study. International Journal of Sport Nutrition and Exercise Metabolism, 25(2), 163–170. https://doi.org/10.1123/ijsnem.2014-0056

Heymsfield, S. B., Thomas, D., Nguyen, A. M., Peng, J. Z., Martin, C., Shen, W., ... & Muller, M. J. (2011). Voluntary weight loss: systematic review of early phase body composition changes. *obesity reviews*, *12*(5), e348-e361. https://doi.org/10.1111/j.1467-789X.2010.00767.x

Heymsfield, S. B., Yang, S., McCarthy, C., Brown, J. B., Martin, C. K., Redman, L. M., ... & Bosy-Westphal, A. (2024). Proportion of caloric restriction-induced weight loss as skeletal muscle. *Obesity*, *32*(1), 32-40. https://doi.org/10.1002/oby.23910

Horswill, C. A., Hickner, R. C., Scott, J. R., Costill, D. L., & Gould, D. (1990). Weight loss, dietary carbohydrate modifications, and high intensity, physical performance. *Medicine and Science in Sports and Exercise*, *22*(4), 470-476. PMID: 2402206

Hsu, C., Huang, Y. W., Lin, S. M., Lu, C. S., Chen, C. Y., & Chang, C. K. (2023). Low-or moderate-carbohydrate calorie–restricted diets have similar effects on body composition and taekwondo performance after high-carbohydrate recovery meals: Low-or moderate-carbohydrate restricted-calorie diets. *European Journal of Sport Science*, (just-accepted), 1-28. https://doi.org/10.1080/17461391.2023.2199423

Humphries, B., Newton, R. U., Bronks, R. O. G. E. R., Marshall, S. O. N. J. A., McBRIDE, J. E. F. F., Triplett- McBride, T. R. A. V. I. S., ... & Sly, N. (2000). Effect of exercise intensity on bone density, strength, and calcium turnover in older women. *Medicine and science in sports and exercise*, *32*(6), 1043-1050. https://doi.org/10.1097/00005768-200006000-00002

Kanaan, M. F., Nait-Yahia, S., & Doucet, É. (2025). The effects of high protein intakes during energy restriction on body composition, energy metabolism and physical performance in recreational athletes. *European Journal of Clinical Nutrition*, 1-9. https://doi.org/10.1038/s41430-025-01585-2

Konstantinides, F. N. (1992). Nitrogen balance studies in clinical nutrition. *Nutrition in Clinical Practice*, *7*(5), 231-238. https://doi.org/10.1177/0115426592007005231

Konopka, A. R., & Harber, M. P. (2014). Skeletal muscle hypertrophy after aerobic exercise training. *Exercise and sport sciences reviews*, *42*(2), 53-61. *DOI:* 10.1249/JES.0000000000000007

Kraemer, W. J., & PENNSYLVANIA STATE UNIV UNIVERSITY PARK. (1997). *Strategies for Optimizing Strength, Power, and Muscle Hypertrophy in Women*. Pennsylvania State University. DOI: 10.21236/ADA348669

Kraemer, W. J., Ratamess, N. A., Flanagan, S. D., Shurley, J. P., Todd, J. S., & Todd, T. C. (2017). Understanding the science of resistance training: An evolutionary perspective. *Sports medicine*, *47*, 2415-2435. https://doi.org/10.1007/s40279-017-0779-y

Kraemer, W. J., Ratamess, N. A., & Rubin, M. R. (2000). Basic principles of resistance training. In *Nutrition and the strength athlete* (pp. 1-21). CRC Press.

Krzysztofik, M., Wilk, M., Wojdała, G., & Gołaś, A. (2019). Maximizing muscle hypertrophy: a systematic review of advanced resistance training techniques and methods. *International journal of environmental research and public health*, *16*(24), 4897. https://doi.org/10.3390/ijerph16244897

Kusinitz, I., & Keeney, C. E. (1958). Effects of progressive weight training on health and physical fitness of adolescent boys. *Research Quarterly. American Association for Health, Physical Education and Recreation*, *29*(3), 294-301. https://doi.org/10.1080/10671188.1958.10762022

Lak, M., Bagheri, R., Ghobadi, H., Campbell, B., Wong, A., Shahrbaf, A., ... & Dutheil, F. (2024). Timing matters? The effects of two different timing of high protein diets on body composition, muscular performance, and biochemical markers in resistance-trained males. *Frontiers in Nutrition*, *11*, 1397090. https://doi.org/10.3389/fnut.2024.1397090

Lalia, C., Ali, A. R., Adel, B., Asli, H., & Othman, B. (2019). Effects of caloric restriction on anthropometrical and specific performance in highly-trained university judo athletes. Physical education of students, 23(1), 30-36. DOI: https://doi.org/10.15561/20755279.2019.010

Lasevicius, T., Schoenfeld, B. J., Silva-Batista, C., de Souza Barros, T., Aihara, A. Y., Brendon, H., ... & Teixeira, E. L. (2022). Muscle failure promotes greater muscle hypertrophy in low-load but not in high-load resistance training. *The Journal of Strength & Conditioning Research*, *36*(2), 346-351. *DOI:* 10.1519/JSC.0000000000003454

Layman, D. K. (2024). Impacts of protein quantity and distribution on body composition. *Frontiers in Nutrition*, *11*, 1388986. https://doi.org/10.3389/fnut.2024.1388986

Lim, C., Nunes, E. A., Currier, B. S., Mcleod, J. C., Thomas, A. C., & Phillips, S. M. (2022). An Evidence-Based Narrative Review of Mechanisms of Resistance Exercise–Induced Human Skeletal Muscle Hypertrophy. *Medicine and science in sports and exercise*, *54*(9), 1546. doi: 10.1249/MSS.0000000000002929

Loenneke, J. P., Rossow, L. M., Fahs, C. A., Thiebaud, R. S., Grant Mouser, J., & Bemben, M. G. (2017). Time-course of muscle growth, and its relationship with muscle strength in both young and older women. *Geriatrics & gerontology international*, *17*(11), 2000-2007. https://doi.org/10.1111/ggi.13010

Longland, T. M., Oikawa, S. Y., Mitchell, C. J., Devries, M. C., & Phillips, S. M. (2016). Higher compared with lower dietary protein during an energy deficit combined with intense exercise promotes greater lean mass gain and fat mass loss: a randomized trial. *The American journal of clinical nutrition*, *103*(3), 738-746. https://doi.org/10.3945/ajcn.115.119339

Longo, A. R., Silva-Batista, C., Pedroso, K., de Salles Painelli, V., Lasevicius, T., Schoenfeld, B. J., ... & Teixeira, E. L. (2022). Volume load rather than resting interval influences muscle hypertrophy during high-intensity resistance training. *The Journal of Strength & Conditioning Research*, *36*(6), 1554-1559. *DOI:* 10.1519/JSC.0000000000003668

Marieb, E. N., & Hoehn, K. (2007). Anatomy and physiology: International edition. *Pearson Education (US)*.

Marston, K. J., Peiffer, J. J., Newton, M. J., & Scott, B. R. (2017). A comparison of traditional and novel metrics to quantify resistance training. *Scientific Reports*, *7*(1), 5606. https://doi.org/10.1038/s41598-017-05953-2

Mazzetti, S. A., Kraemer, W. J., Volek, J. S., Duncan, N. D., Ratamess, N. A., Gómez, A. L., ... & Fleck, S. J. (2000). The influence of direct supervision of resistance training on strength performance. *Medicine and science in sports and exercise*, *32*(6), 1175-1184. https://doi.org/10.1097/00005768-200006000-00023

McBride, J. M., McCaulley, G. O., Cormie, P., Nuzzo, J. L., Cavill, M. J., & Triplett, N. T. (2009). Comparison of methods to quantify volume during resistance exercise. *The Journal of Strength & Conditioning Research*, *23*(1), 106-110. *DOI:* 10.1519/JSC.0b013e31818efdfe

Melzer, K. (2011). Carbohydrate and fat utilization during rest and physical activity. *e-SPEN, the European e-Journal of Clinical Nutrition and Metabolism*, *6*(2), e45-e52. https://doi.org/10.1016/j.eclnm.2011.01.005

Mettler, S., Mitchell, N., & Tipton, K. D. (2010). Increased protein intake reduces lean body mass loss during weight loss in athletes. *Medicine & Science in Sports & Exercise*, *42*(2), 326-337. DOI: 10.1249/MSS.0b013e3181b2ef8e

Mitchell, L., Slater, G., Hackett, D., Johnson, N., & O'connor, H. (2018). Physiological implications of preparing for a natural male bodybuilding competition. *European journal of sport science*, *18*(5), 619-629. https://doi.org/10.1080/17461391.2018.1444095

Morton, R. W., Murphy, K. T., McKellar, S. R., Schoenfeld, B. J., Henselmans, M., Helms, E., ... & Phillips, S. M. (2018). A systematic review, meta-analysis and meta-regression of the effect of protein supplementation on resistance training-induced gains in muscle mass and strength in healthy adults. *British journal of sports medicine*, *52*(6), 376-384. http://dx.doi.org/10.1136/

Ogasawara, R., Loenneke, J. P., Thiebaud, R. S., & Abe, T. (2013). Low-load bench press training to fatigue results in muscle hypertrophy similar to high-load bench press training. *International Journal of Clinical Medicine*, *4*(02), 114-121. https://doi.org/10.4236/ijcm.2013.42022

Parolin, M. L., Chesley, A., Matsos, M. P., Spriet, L. L., Jones, N. L., & Heigenhauser, G. J. (1999). Regulation of skeletal muscle glycogen phosphorylase and PDH during maximal intermittent exercise. *American Journal of Physiology-Endocrinology and Metabolism*. https://doi.org/10.1152/ajpendo.1999.277.5.E890

Pasiakos, S. M., Cao, J. J., Margolis, L. M., Sauter, E. R., Whigham, L. D., McClung, J. P., ... & Young, A. J. (2013). Effects of high protein diets on fat-free mass and muscle protein synthesis following weight loss: a randomized controlled trial. DOI: 10.1096/fj.13-230227

Pasiakos, S. M., Margolis, L. M., McClung, J. P., Cao, J. J., Whigham, L. D., Combs, G. F., & Young, A. J. (2014). Whole-body protein turnover response to short-term high-protein diets during weight loss: a randomized controlled trial. *International journal of obesity*, *38*(7), 1015-1018. https://doi.org/10.1038/ijo.2013.197

Pearson, D., Faigenbaum, A., Conley, M., & Kraemer, W. J. (2000). The National Strength and Conditioning Association's basic guidelines for the resistance training of athletes. *Strength & Conditioning Journal*, *22*(4), 14.

Phillips, S. M., & Van Loon, L. J. (2013). Dietary protein for athletes: from requirements to optimum adaptation. *Food, Nutrition and Sports Performance III*, 29-38. https://doi.org/10.1080/02640414.2011.619204

Pons, V., Riera, J., Capó, X., Martorell, M., Sureda, A., Tur, J. A., ... & Pons, A. (2018). Calorie restriction regime enhances physical performance of trained athletes. *Journal of the International Society of Sports Nutrition*, *15*(1), 12. https://doi.org/10.1186/s12970-018-0214-2

Powell, J. J., Tucker, L., Fisher, A. G., & Wilcox, K. (1994). The effects of different percentages of dietary fat intake, exercise, and calorie restriction on body composition and body weight in obese females. *American journal of health promotion*, *8*(6), 442-448. https://doi.org/10.4278/0890-1171-8.6.442

Refalo, M. C., Trexler, E. T., & Helms, E. R. (2022). Effect of Dietary Protein on Fat-Free Mass in Energy Restricted, Resistance-Trained Individuals: An Updated Systematic Review With Meta-Regression. *Strength & Conditioning Journal*, 10-1519. *DOI:* 10.1519/SSC.0000000000000888

Remmert, J., Pelland, J., Robinson, Z., Hinson, S., & Zourdos, M. Is There Too Much of a Good Thing? Meta-Regressions of the Effect of Per-Session Volume on Hypertrophy and Strength. DOI**:** https://doi.org/10.51224/SRXIV.537

Richard Berger, "Effects of Strength Improvement on Accuracy in a Gross Motor Task," American Corrective Therapy, 27 (March-April 1973): 57-58. PMID: 4707127

Roberts, J., Zinchenko, A., Suckling, C., Smith, L., Johnstone, J., & Henselmans, M. (2017). The short-term effect of high versus moderate protein intake on recovery after strength training in resistance-trained individuals. *Journal of the International Society of Sports Nutrition*, *14*, 1-11. https://doi.org/10.1186/s12970-017-0201-z

Roberts, M. D., McCarthy, J. J., Hornberger, T. A., Phillips, S. M., Mackey, A. L., Nader, G. A., ... & Esser, K. A. (2023). Mechanisms of mechanical overload-induced skeletal muscle hypertrophy: current understanding and future directions. *Physiological reviews*. https://doi.org/10.1152/physrev.00039.2022

Roth, C., Schoenfeld, B. J., & Behringer, M. (2022). Lean mass sparing in resistance-trained athletes during caloric restriction: the role of resistance training volume. *European journal of applied physiology*, *122*(5), 1129-1151. https://doi.org/10.1007/s00421-022-04896-5

Roth, C., Schwiete, C., Happ, K., Rettenmaier, L., Schoenfeld, B. J., & Behringer, M. (2023). Resistance training volume does not influence lean mass preservation during energy restriction in trained males. *Scandinavian Journal of Medicine & Science in Sports*, *33*(1), 20-35. https://doi.org/10.1111/sms.14237 =

Sampson JA, Groeller H. Is repetition failure critical for the development of muscle hypertrophy and strength? Scand J Med Sci Sports 26: 375–383, 2016. https://doi.org/10.1111/sms.12445

Saric, J., Lisica, D., Orlic, I., Grgic, J., Krieger, J. W., Vuk, S., & Schoenfeld, B. J. (2019). Resistance training frequencies of 3 and 6 times per week produce similar muscular adaptations in resistance-trained men. *The Journal of Strength & Conditioning Research*, *33*, S122-S129. *DOI:* 10.1519/JSC.0000000000002909

Scarpelli, M. C., Nóbrega, S. R., Santanielo, N., Alvarez, I. F., Otoboni, G. B., Ugrinowitsch, C., & Libardi, C. A. (2022). Muscle hypertrophy response is affected by previous resistance training volume in trained individuals. *Journal of Strength and Conditioning Research*, *36*(4), 1153-1157. *DOI:* 10.1519/JSC.0000000000003558

Schiaffino, S., Reggiani, C., Akimoto, T., & Blaauw, B. (2021). Molecular mechanisms of skeletal muscle hypertrophy. *Journal of neuromuscular diseases*, *8*(2), 169-183. https://doi.org/10.3233/JND-200568

Schoenfeld, B. J. (2020). *Science and development of muscle hypertrophy*. Human Kinetics.

Schoenfeld, B. J. (2010). The mechanisms of muscle hypertrophy and their application to resistance training. *The Journal of Strength & Conditioning Research*, *24*(10), 2857-2872. DOI: 10.1519/JSC.0b013e3181e840f3

Schoenfeld, B. J., Alto, A., Grgic, J., Tinsley, G., Haun, C. T., Campbell, B. I., ... & Trexler, E. T. (2020). Alterations in body composition, resting metabolic rate, muscular strength, and eating behavior in response to natural bodybuilding competition preparation: a case study. *The Journal of Strength & Conditioning Research*, *34*(11), 3124-3138. *DOI:* 10.1519/JSC.0000000000003816

Schoenfeld, B. J., & Aragon, A. A. (2018). Is there a postworkout anabolic window of opportunity for nutrient consumption? Clearing up controversies. *journal of orthopaedic & sports physical therapy*, *48*(12), 911-914. https://www.jospt.org/doi/10.2519/jospt.2018.0615

Schoenfeld, B. J., Contreras, B., Krieger, J., Grgic, J., Delcastillo, K., Belliard, R., & Alto, A. (2018). Resistance training volume enhances muscle hypertrophy but not strength in trained men. *Medicine and science in sports and exercise*, *51*(1), 94. doi: 10.1249/MSS.0000000000001764

Schoenfeld, B., Fisher, J., Grgic, J., Haun, C., Helms, E., Phillips, S., ... & Vigotsky, A. (2021). Resistance training recommendations to maximize muscle hypertrophy in an athletic population: Position stand of the IUSCA. *International Journal of Strength and Conditioning*, *1*(1). https://doi.org/10.47206/ijsc.v1i1.81

Schoenfeld, B. J., Grgic, J., Ogborn, D., & Krieger, J. W. (2017). Strength and hypertrophy adaptations between low-vs. high-load resistance training: a systematic review and meta-analysis. *The Journal of Strength & Conditioning Research*, *31*(12), 3508-3523. *DOI:* 10.1519/JSC.0000000000002200

Schoenfeld, B. J., Grgic, J., Van Every, D. W., & Plotkin, D. L. (2021). Loading recommendations for muscle strength, hypertrophy, and local endurance: a re-examination of the repetition continuum. *Sports*, *9*(2), 32. https://doi.org/10.3390/sports9020032

Schoenfeld, B. J., Peterson, M. D., Ogborn, D., Contreras, B., & Sonmez, G. T. (2015). Effects of low-vs. high-load resistance training on muscle strength and hypertrophy in well-trained men. *The Journal of Strength & Conditioning Research*, *29*(10), 2954-2963. *DOI:* 10.1519/JSC.0000000000000958

Schoenfeld, B. J., Ogborn, D., & Krieger, J. W. (2017). The dose–response relationship between resistance training volume and muscle hypertrophy: are there really still any doubts?. *Journal of sports sciences*, *35*(20), 1985-1987. https://doi.org/10.1080/02640414.2016.1243800

Schoenfeld, B. J., Ogborn, D. I., & Krieger, J. W. (2015). Effect of repetition duration during resistance training on muscle hypertrophy: a systematic review and meta-analysis. *Sports Medicine*, *45*, 577-585. https://doi.org/10.1007/s40279-015-0304-0

Schoenfeld, B. J., Ogborn, D. I., Vigotsky, A. D., Franchi, M. V., & Krieger, J. W. (2017). Hypertrophic effects of concentric vs. eccentric muscle actions: a systematic review and meta-analysis. *The Journal of Strength & Conditioning Research*, *31*(9), 2599-2608. *DOI:* 10.1519/JSC.0000000000001983

Siedler, M. R., Harty, P. S., Stratton, M. T., Rodriguez, C., Keith, D., Green, J., ... & Tinsley, G. M. (2021). Day-to-day precision error and least significant change for two commonly used bioelectrical impedance analysis devices. In *International Journal of Exercise Science: Conference Proceedings* (Vol. 2, No. 13, p. 18).

Singer, A., Wolf, M., Generoso, L., Arias, E., Delcastillo, K., Echevarria, E., ... & Schoenfeld, B. J. (2024). Give it a rest: a systematic review with Bayesian meta-analysis on the effect of inter-set rest interval duration on muscle hypertrophy. *Frontiers in sports and active living*. https://doi.org/10.3389/fspor.2024.1429789

Starkey, D. B., Pollock, M. L., Ishida, Y., Welsch, M. A., Brechue, W. F., Graves, J. E., & Feigenbaum, M. S. (1996). Effect of resistance training volume on strength and muscle thickness. *Medicine and science in sports and exercise*, *28*(0), 10. DOI: 10.1097/00005768-199610000-00016

Stojiljković, N., Ignjatović, A., Savić, Z., Marković, Ž., & Milanović, S. (2013). History of resistance training. *Activities Phys Educ Sport*, *3*(1), 135-8.

Suchomel, T. J., Wagle, J. P., Douglas, J., Taber, C. B., Harden, M., Haff, G. G., & Stone, M. H. (2019). Implementing eccentric resistance training—Part 1: A brief review of existing methods. *Journal of Functional Morphology and Kinesiology*, *4*(2), 38. https://doi.org/10.3390/jfmk4020038

Terzis, G., Spengos, K., Mascher, H., Georgiadis, G., Manta, P., & Blomstrand, E. (2010). The degree of p70 S6k and S6 phosphorylation in human skeletal muscle in response to resistance exercise depends on the training volume. *European Journal of Applied Physiology*, 110(4), 835–843. doi:10.1007/s00421-010-1527-2

Tinsley, G. M., Trexler, E. T., Smith-Ryan, A. E., Paoli, A., Graybeal, A. J., Campbell, B. I., & Schoenfeld, B. J. (2019). Changes in body composition and neuromuscular performance through preparation, 2 competitions, and a recovery period in an experienced female physique athlete. *The Journal of Strength & Conditioning Research*, *33*(7), 1823-1839. DOI*:* 10.1519/JSC.0000000000002758

TODD, T., & TODD, J. (2013). The Science of Reps: The Strength Training Contributions of Dr. Richard A. Berger. *Iron Game History*, *12*(2).

Van der Ploeg, G. E., Brooks, A. G., Withers, R. T., Dollman, J., Leaney, F., & Chatterton, B. E. (2001). Body composition changes in female bodybuilders during preparation for competition. European journal of clinical nutrition, 55(4), 268-277. https://doi.org/10.1038/sj.ejcn.1601154

Vargas-Molina, S., Petro, J. L., Romance, R., Kreider, R. B., Schoenfeld, B. J., Bonilla, D. A., & Benítez-Porres, J. (2020). Effects of a ketogenic diet on body composition and strength in trained women. Journal of the International Society of Sports Nutrition, 17(1), 19. https://doi.org/10.1186/s12970-020-00348-7

Vann, C. G., Sexton, C. L., Osburn, S. C., Smith, M. A., Haun, C. T., Rumbley, M. N., ... & Roberts, M. D. (2022). Effects of high-volume versus high-load resistance training on skeletal muscle growth and molecular adaptations. *Frontiers in Physiology*, *13*, 857555. https://doi.org/10.3389/fphys.2022.857555

Vink, R. G., Roumans, N. J., Arkenbosch, L. A., Mariman, E. C., & van Baak, M. A. (2016). The effect of rate of weight loss on long-term weight regain in adults with overweight and obesity. *Obesity*, *24*(2), 321-327. https://doi.org/10.1002/oby.21346

Volek, J. S., Kraemer, W. J., Bush, J. A., Incledon, T., & Boetes, M. (1997). Testosterone and cortisol in relationship to dietary nutrients and resistance exercise. *Journal of Applied Physiology*. https://doi.org/10.1152/jappl.1997.82.1.49

von Loeffelholz, C., & Birkenfeld, A. L. (2022). Non-exercise activity thermogenesis in human energy homeostasis. *Endotext [Internet]*. https://doi.org/10.1053/beem.2002.0227

Weinheimer, E. M., Sands, L. P., & Campbell, W. W. (2010). A systematic review of the separate and combined effects of energy restriction and exercise on fat-free mass in middle-aged and older adults: implications for sarcopenic obesity. *Nutrition reviews*, *68*(7), 375-388. https://doi.org/10.1111/j.1753-4887.2010.00298.x

Wernbom, M., Augustsson, J., & Thomeé, R. (2007). The influence of frequency, intensity, volume and mode of strength training on whole muscle cross-sectional area in humans. *Sports medicine*, *37*, 225-264. https://doi.org/10.2165/00007256-200737030-00004

Wilk, M., Zajac, A., & Tufano, J. J. (2021). The influence of movement tempo during resistance training on muscular strength and hypertrophy responses: a review. *Sports medicine*, *51*(8), 1629-1650. https://doi.org/10.1007/s40279-021-01465-2

Witard, O. C., Bannock, L., & Tipton, K. D. (2021). Making sense of muscle protein synthesis: a focus on muscle growth during resistance training. *International journal of sport nutrition and exercise metabolism*, *32*(1), 49-61. https://doi.org/10.1123/ijsnem.2021-0139

Yasuda, J., Tomita, T., Arimitsu, T., & Fujita, S. (2020). Evenly distributed protein intake over 3 meals augments resistance exercise–induced muscle hypertrophy in healthy young men. *The Journal of nutrition*, *150*(7), 1845-1851. https://doi.org/10.1093/jn/nxaa101

Supplemental material

Figure 1. Example of the prescribed diet plan.

FOOD

EQUIVALENTS

- ***The following pages describe food quantities which correspond to equivalents in each of the food groups.***

<u>Your personalized plan :</u>

- ***You will find at the beginning of each food group a number of equivalents that you must consume everyday to attein your goal.***

Notes

Macros : Protein X/Carbohydrates Y/Fat Z

Vegetables ☐ equivalents/day

One equivalent correspond to :

- Juice : tomatoes, vegetables, carrots..........125 ml (1/2 cup)
- Winter squash, mixed vegetables, green peas, parsnips ....75 ml (1/3 cup)
- Artichoke heart, artichoke..........................125 ml (1/2 moyen)
- Beats, carrots, Brussel sprouts, pumpkin puree, oinions, leaks, peas, asparagus, brocolli, cabbage, cauliflower, summer squash, zucchini, endives, spinach (warm), chives, yellow or green beans, canned tomatoes, turnip.....................125 ml (1/2 cup)
- Diced eggplant...250 ml (1 cup)

Vegetables with high % of water

- Celery, mushrooms, cucumber, fiddle head, raw spinach, bean sprouts, alfalfa sprouts, radish, lettuce, peppers, tomatoes..................500 ml (2 cups)

Fruits ☐ equivalents/day

One equivalent correspond to :

- Apricots, kiwi, dattes, fig, clementines, prunes...........................2 fruits
- Fruit compotes, salads or jus and canned fruit (unswettened)......................125 ml (1/2 cup)
- Banana, mangoes, kaki, grapefruit, papaya..1/2 fruit
- Nectarine, orange, peach, pear, apple, tangerine..............................1 fruit
- Cantaloup..1/4 fruit
- Honeydew..1/8 fruit
- Strawberries, currant, rasberries, water melon, honeydew..............................250 ml (1 cup)
- Rhubarbe...500 ml (2 cup)

Grain products ☐ equivalents/day

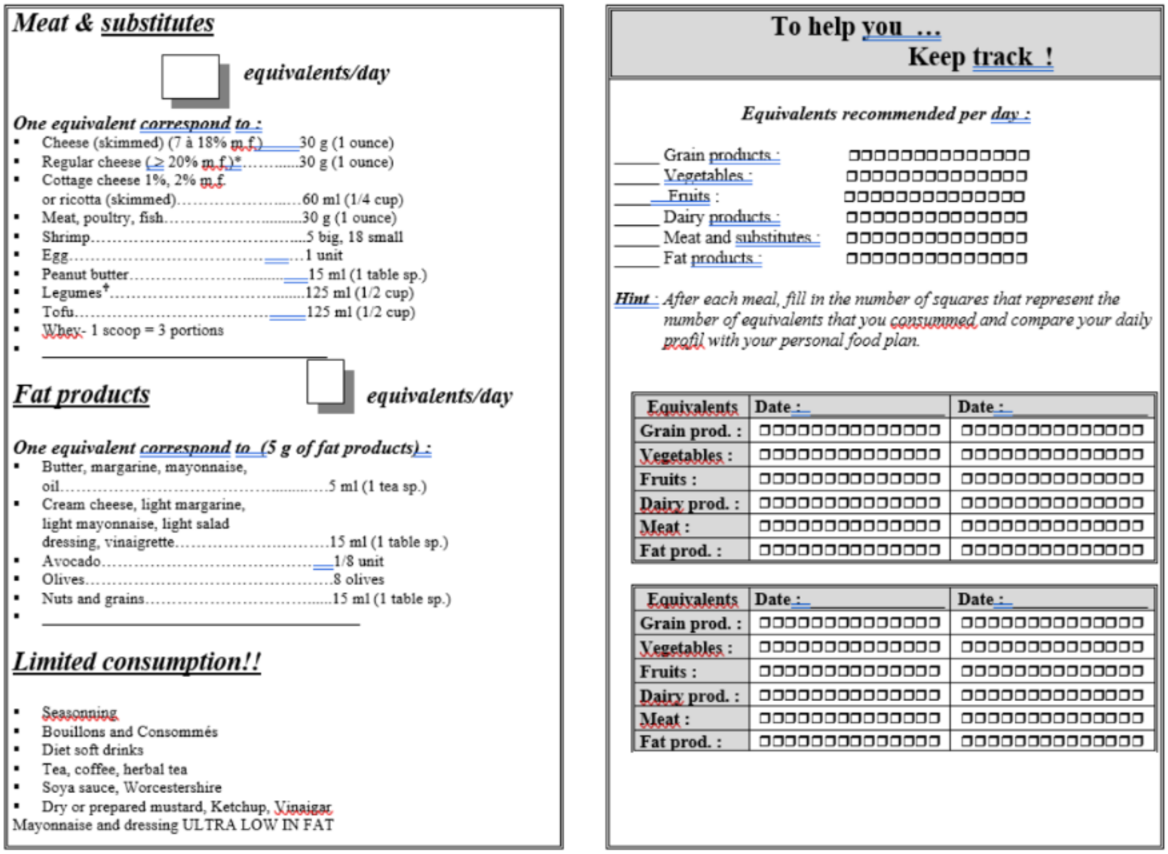
One equivalent correspond to :

- Toasted bread, dry crackers (all kinds)..........2 units
- Soda Crackers, Melba...............................5 units
- Breakfast cereals (warm or ready to serve, little or no sugar).............................30 g (3/4 cup)
- Rice, couscous, pasta, mashed potatoes, corn..................................125 ml (1/2 cup)
- Popcorn (no butter)....................................750 ml (3 cups)
- Hamburger or hot dogs buns, bagel English muffin, Keiser, pita.....................1/2 unit
- Sliced bread, small salad bread.....................1 unit
- Baguette 1½ slice..................................4 units
- Pasta soup...250 ml (1 cup)
- Pea soup...125 ml (1/2 cup)
- ______________________________
- ______________________________
- ______________________________

Dairy Products ☐ equivalents/day

One equivalent correspond to

- Milk 2%, 1% or skimmed..........................250 ml
- Yogurt < 2% m.f......................................175 ml
- Unswettened evaporated milk (Carnation).........100 ml
- Ice cream...250 ml
- Powdered milk...60 ml
- ______________________________
- ______________________________
- ______________________________
- ______________________________



Meat & substitutes

☐ equivalents/day

One equivalent correspond to :

- Cheese (skimmed) (7 à 18% m.f.)........30 g (1 ounce)
- Regular cheese (≥ 20% m.f.)*............30 g (1 ounce)
- Cottage cheese 1%, 2% m.f.
  or ricotta (skimmed)........................60 ml (1/4 cup)
- Meat, poultry, fish..............................30 g (1 ounce)
- Shrimp..5 big, 18 small
- Egg...1 unit
- Peanut butter.......................................15 ml (1 table sp.)
- Legumes†...125 ml (1/2 cup)
- Tofu..125 ml (1/2 cup)
- Whey- 1 scoop = 3 portions
- ______________________________

Fat products

☐ equivalents/day

One equivalent correspond to (5 g of fat products) :

- Butter, margarine, mayonnaise,
  oil..5 ml (1 tea sp.)
- Cream cheese, light margarine,
  light mayonnaise, light salad
  dressing, vinaigrette..............................15 ml (1 table sp.)
- Avocado...1/8 unit
- Olives...8 olives
- Nuts and grains......................................15 ml (1 table sp.)
- ______________________________

Limited consumption!!

- Seasonning
- Bouillons and Consommés
- Diet soft drinks
- Tea, coffee, herbal tea
- Soya sauce, Worcestershire
- Dry or prepared mustard, Ketchup, Vinaigar

Mayonnaise and dressing ULTRA LOW IN FAT

To help you …
Keep track !

Equivalents recommended per day :

_____ Grain products : ☐☐☐☐☐☐☐☐☐☐☐☐☐☐
_____ Vegetables : ☐☐☐☐☐☐☐☐☐☐☐☐☐☐
_____ Fruits : ☐☐☐☐☐☐☐☐☐☐☐☐☐☐
_____ Dairy products : ☐☐☐☐☐☐☐☐☐☐☐☐☐☐
_____ Meat and substitutes : ☐☐☐☐☐☐☐☐☐☐☐☐☐☐
_____ Fat products : ☐☐☐☐☐☐☐☐☐☐☐☐☐☐

Hint *: After each meal, fill in the number of squares that represent the number of equivalents that you consummed and compare your daily profil with your personal food plan.*

Equivalents	Date :	Date :
Grain prod. :	☐☐☐☐☐☐☐☐☐☐☐☐☐☐	☐☐☐☐☐☐☐☐☐☐☐☐☐☐
Vegetables :	☐☐☐☐☐☐☐☐☐☐☐☐☐☐	☐☐☐☐☐☐☐☐☐☐☐☐☐☐
Fruits :	☐☐☐☐☐☐☐☐☐☐☐☐☐☐	☐☐☐☐☐☐☐☐☐☐☐☐☐☐
Dairy prod. :	☐☐☐☐☐☐☐☐☐☐☐☐☐☐	☐☐☐☐☐☐☐☐☐☐☐☐☐☐
Meat :	☐☐☐☐☐☐☐☐☐☐☐☐☐☐	☐☐☐☐☐☐☐☐☐☐☐☐☐☐
Fat prod. :	☐☐☐☐☐☐☐☐☐☐☐☐☐☐	☐☐☐☐☐☐☐☐☐☐☐☐☐☐

Equivalents	Date :	Date :
Grain prod. :	☐☐☐☐☐☐☐☐☐☐☐☐☐☐	☐☐☐☐☐☐☐☐☐☐☐☐☐☐
Vegetables :	☐☐☐☐☐☐☐☐☐☐☐☐☐☐	☐☐☐☐☐☐☐☐☐☐☐☐☐☐
Fruits :	☐☐☐☐☐☐☐☐☐☐☐☐☐☐	☐☐☐☐☐☐☐☐☐☐☐☐☐☐
Dairy prod. :	☐☐☐☐☐☐☐☐☐☐☐☐☐☐	☐☐☐☐☐☐☐☐☐☐☐☐☐☐
Meat :	☐☐☐☐☐☐☐☐☐☐☐☐☐☐	☐☐☐☐☐☐☐☐☐☐☐☐☐☐
Fat prod. :	☐☐☐☐☐☐☐☐☐☐☐☐☐☐	☐☐☐☐☐☐☐☐☐☐☐☐☐☐

Figure 2. Prescribed lower-body (a) and upper-body (b) programs in HVRT (1) and LVRT (2), respectively

1a.

Lower Body

1 - Bb Front Squat

- Garder le dos droit - Poitrine sortie - Tête droite - Garder les abdominaux tendus

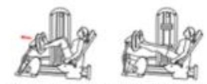
Sem.	Séries	Rep	Tempo	Charge	Repos
1-4	5	10 - 12	2-0-2-0		01:30

2 - DB Stiff Leg Deadlift

- Debout, tenir un dumbbell devant vous dans chaque main. Vous tenir debout les pieds sous les épaules. Tout en gardant le dos droit et la tête droite, engager vos hanches en dirigeant vos fessiers vers l'arrière et descendre le corps vers l'avant, dos parallèle au sol. Revenir à la position de départ en gardant le corps bien engagé et en travaillant en contrôle.

Sem.	Séries	Rep	Tempo	Charge (kg)	Repos
1-4	5	10 - 12	2-0-2-0		01:30

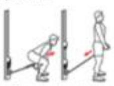
3 - Machine Single Leg Press Horizontal



- Assis, le dos droit appuyé sur le dossier, placer les pieds à la largeur des épaules sur l'appui, les genoux à environ 90°. Pousser vers l'avant en extension complète des genoux et revenir à la position de départ. Garder les abdos contractés.

Sem.	Séries	Rep	Tempo	Charge (kg)	Repos
1-4	5	10 - 12	2-0-2-0		01:30

4 - Tirage bas arrière vers avant sur poulie



- Passer le câble entre vos jambes en tenant le câble derrière vos genoux. Faire un Squat, genoux à environ 90°, en amenant vos mains devant vos hanches. Garder le dos droit, les abdos contractés et la tête haute.

Sem.	Séries	Rep	Tempo	Charge (kg)	Repos
1-4	5	10 - 12	2-0-2-0		01:30

5 - Extension de genou sur machine

- Assis, le dos à plat sur le dossier, faire des extensions de genoux. Placer les appuis sur les chevilles. Garder les genoux alignés avec le pivot du levier. Garder les abdos tendus.

Sem.	Séries	Rep	Tempo	Charge (kg)	Repos
1-4	5	10 - 12	2-0-2-0		01:30

6 - Leg Curl sur machine

- Placer les chevilles sous les appuis. Faire des flexions de genoux en gardant un angle de 90° aux chevilles. Garder le dos droit et vos abdos tendus.

Sem.	Séries	Rep	Tempo	Charge (kg)	Repos
1-4	5	10 - 12	2-0-2-0		01:30

7 - Plate Russian Twist

- En équilibre sur les fesses, les jambes allongées devant vous, déposer un poids (plate) d'un côté et de l'autre de vos hanches en tournant les épaules. Garder vos abdos contractés.

Sem.	Séries	Rep	Tempo	Charge (kg)	Repos
1-4	3	10 - 12	2-0-2-0		01:30

1b.

Upper Body

1 - Développé pectoraux sur machine

- Le dos à plat sur le banc et la tête haute, pousser vers l'avant jusqu'à extension complète des bras.

Sem.	Séries	Rep	Tempo	Charge (kg)	Repos
1-4	5	10 - 12	2-0-2-0		01:30

2 - Seated Row Machine

- Assis sur le siège de la machine, ajuster l'appui ventral de manière à avoir les bras en complète extension lors de la tenue des poignées. Tenir les poignées en prise pronation (paumes de mains vers le bas). Tout en gardant les avant-bras à l'horizontale, tirer sur les poignées en amenant les omoplates l'une vers l'autre. Garder le dos droit et la tête haute.

Sem.	Séries	Rep	Tempo	Charge	Repos
1-4	5	10 - 12	2-0-2-0		01:30

3 - Bb Military Press debout

- Debout, les pieds à la largeur des épaules, les genoux légèrement fléchis, tenir la barre au niveau des épaules, les mains alignées avec les épaules, poussez la barre au-dessus de votre tête. Garder les abdos contractés et le dos droit.

Sem.	Séries	Rep	Tempo	Charge (kg)	Repos
1-4	5	10 - 12	2-0-2-0		01:30

4 - Fly Pec Deck

- Assis dans la machine "Pec Deck", tenir les poignées avec les coudes alignés avec les épaules. Tout en gardant votre dos à plat et les coudes légèrement fléchis, amener vos mains l'une vers l'autre et retourner à la position de départ. Répéter.

Sem.	Séries	Rep	Tempo	Charge (kg)	Repos
1-4	5	10 - 12	2-0-2-0		01:30

5 - Lat pulldown incliné prise pronation

- Prise pronation - Garder le dos droit

Sem.	Séries	Rep	Tempo	Charge (kg)	Repos
1-4	5	10 - 12	2-0-2-0		01:30

6 - Stand DB Side Raise

- Garder le dos droit, les abdos tendus, la tête haute et les genoux légèrement fléchis. Coudes légèrement fléchis. Lever les coudes à la hauteur des épaules. Prise neutre ou marteau.

Sem.	Séries	Rep	Tempo	Charge (kg)	Repos
1-4	5	10 - 12	2-0-2-0		01:30

7 - Debout Barbell Biceps Curl

- Les pieds à la largeur des épaules, faire des flexions de coudes en tenant la barre avec les mains à la largeur des épaules prise supination (paume vers l'avant). Garder les abdos tendus et le dos droit.

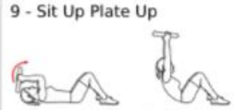
Sem.	Séries	Rep	Tempo	Charge (kg)	Repos
1-4	5	10 - 12	2-0-2-0		01:30

8 - Extension coudes poulie avec corde

- Garder les abdos contractés et le dos droit. Faire des extensions des coudes. Prise neutre avec corde.

Sem.	Séries	Rep	Tempo	Charge (kg)	Repos
1-4	5	10 - 12	2-0-2-0		01:30

9 - Sit Up Plate Up



- Débuter couché sur le dos, les pieds au sol. Tenir un poids (plate) les coudes à 90° alignés avec vos épaules. Faire un sit up en soulevant la charge vers le ciel. Revenir à la position de départ en faisant le mouvement inverse. Garder vos abdos contractés.

Sem.	Séries	Rep	Tempo	Charge (kg)	Repos
1-4	3	10 - 12	2-0-2-0		01:30

2a.

Lower Body

1 - Bb Front Squat

- Garder le dos droit - Poitrine sortie - Tête droite - Garder les abdominaux tendus

Sem.	Séries	Rep	Tempo	Charge	Repos
1-4	2	10 - 12	2-0-2-0		01:30

2 - DB Stiff Leg Deadlift

- Debout, tenir un dumbbell devant vous dans chaque main. Vous tenir debout les pieds sous les épaules. Tout en gardant le dos droit et la tête droite, engager vos hanches en dirigeant vos fessiers vers l'arrière et descendre le corps vers l'avant, dos parallèle au sol. Revenir à la position de départ en gardant le corps bien engagé et en travaillant en contrôle.

Sem.	Séries	Rep	Tempo	Charge (kg)	Repos
1-4	2	10 - 12	2-0-2-0		01:30

3 - Machine Single Leg Press Horizontal

- Assis, le dos droit appuyé sur le dossier, placer les pieds à la largeur des épaules sur l'appui, les genoux à environ 90°. Pousser vers l'avant en extension complète des genoux et revenir à la position de départ. Garder les abdos contractés.

Sem.	Séries	Rep	Tempo	Charge (kg)	Repos
1-4	2	10 - 12	2-0-2-0		01:30

4 - Tirage bas arrière vers avant sur poulie

- Passer le câble entre vos jambes en tenant le câble derrière vos genoux. Faire un Squat, genoux à environ 90°, en amenant vos mains devant vos hanches. Garder le dos droit, les abdos contractés et la tête haute.

Sem.	Séries	Rep	Tempo	Charge (kg)	Repos
1-4	2	10 - 12	2-0-2-0		01:30

5 - Extension de genou sur machine

- Assis, le dos à plat sur le dossier, faire des extensions de genoux. Placer les appuis sur les chevilles. Garder les genoux alignés avec le pivot du levier. Garder les abdos tendus.

Sem.	Séries	Rep	Tempo	Charge (kg)	Repos
1-4	2	10 - 12	2-0-2-0		01:30

6 - Leg Curl sur machine

- Placer les chevilles sous les appuis. Faire des flexions de genoux en gardant un angle de 90° aux chevilles. Garder le dos droit et vos abdos tendus.

Sem.	Séries	Rep	Tempo	Charge (kg)	Repos
1-4	2	10 - 12	2-0-2-0		01:30

supporté par

[redacted]

Samir Nait-Yahia (#0051012668-0)
Lower Body LRTV, Samir Nait-Yahia

7 - Plate Russian Twist

- En équilibre sur les fesses, les jambes allongées devant vous, déposer un poids (plate) d'un côté et de l'autre de vos hanches en tournant les épaules. Garder vos abdos contractés.

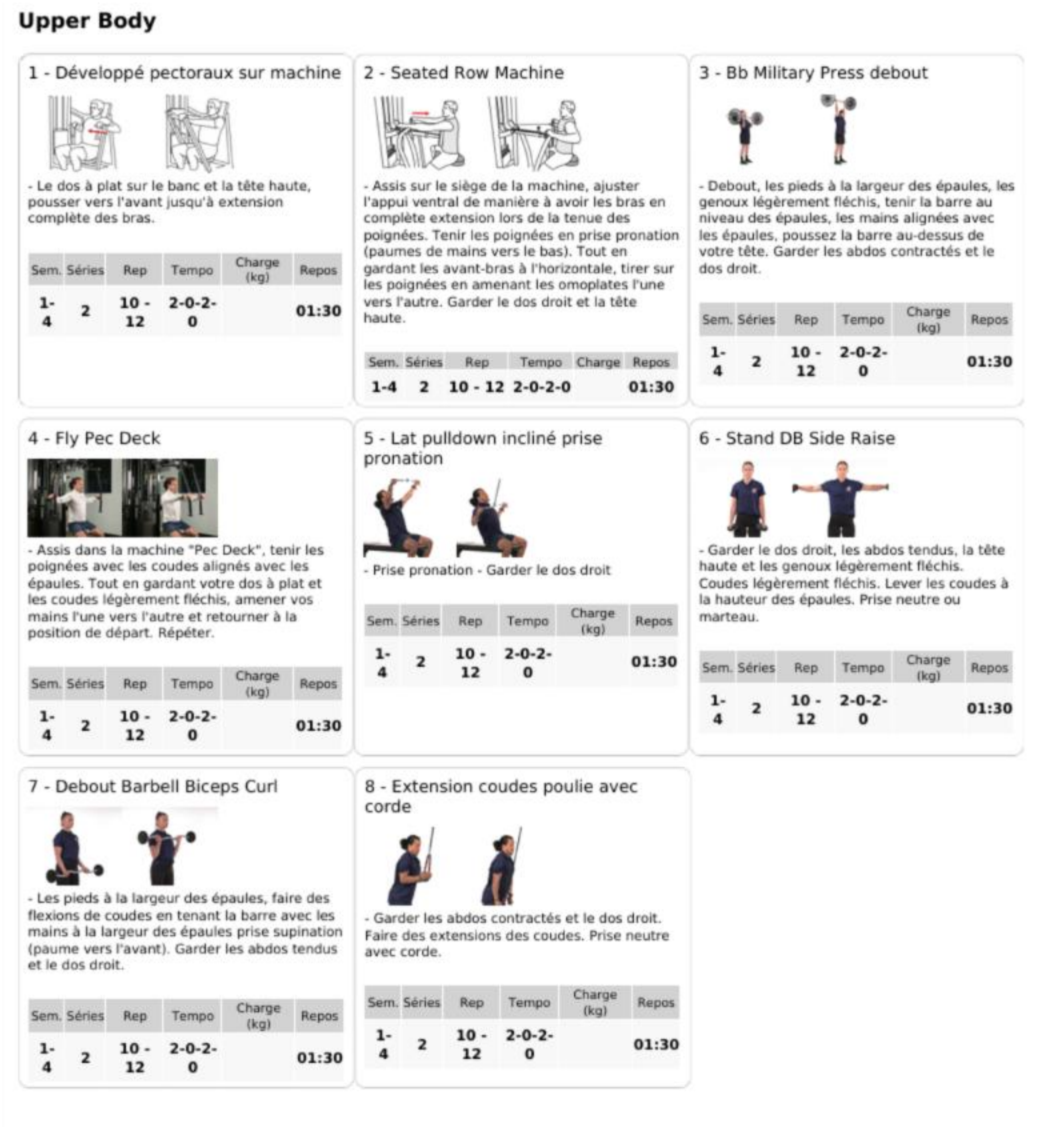
Sem.	Séries	Rep	Tempo	Charge (kg)	Repos
1-4	2	10 - 12	2-0-2-0		01:30

8 - Sit Up Plate Up

- Débuter couché sur le dos, les pieds au sol. Tenir un poids (plate) les coudes à 90° alignés avec vos épaules. Faire un sit up en soulevant la charge vers le ciel. Revenir à la position de départ en faisant le mouvement inverse. Garder vos abdos contractés.

Sem.	Séries	Rep	Tempo	Charge (kg)	Repos
1-4	1	10 - 12	2-0-2-0		01:30

2b.



Upper Body

1 - Développé pectoraux sur machine

- Le dos à plat sur le banc et la tête haute, pousser vers l'avant jusqu'à extension complète des bras.

Sem.	Séries	Rep	Tempo	Charge (kg)	Repos
1-4	2	10 - 12	2-0-2-0		01:30

2 - Seated Row Machine

- Assis sur le siège de la machine, ajuster l'appui ventral de manière à avoir les bras en complète extension lors de la tenue des poignées. Tenir les poignées en prise pronation (paumes de mains vers le bas). Tout en gardant les avant-bras à l'horizontale, tirer sur les poignées en amenant les omoplates l'une vers l'autre. Garder le dos droit et la tête haute.

Sem.	Séries	Rep	Tempo	Charge	Repos
1-4	2	10 - 12	2-0-2-0		01:30

3 - Bb Military Press debout

- Debout, les pieds à la largeur des épaules, les genoux légèrement fléchis, tenir la barre au niveau des épaules, les mains alignées avec les épaules, poussez la barre au-dessus de votre tête. Garder les abdos contractés et le dos droit.

Sem.	Séries	Rep	Tempo	Charge (kg)	Repos
1-4	2	10 - 12	2-0-2-0		01:30

4 - Fly Pec Deck

- Assis dans la machine "Pec Deck", tenir les poignées avec les coudes alignés avec les épaules. Tout en gardant votre dos à plat et les coudes légèrement fléchis, amener vos mains l'une vers l'autre et retourner à la position de départ. Répéter.

Sem.	Séries	Rep	Tempo	Charge (kg)	Repos
1-4	2	10 - 12	2-0-2-0		01:30

5 - Lat pulldown incliné prise pronation

- Prise pronation - Garder le dos droit

Sem.	Séries	Rep	Tempo	Charge (kg)	Repos
1-4	2	10 - 12	2-0-2-0		01:30

6 - Stand DB Side Raise

- Garder le dos droit, les abdos tendus, la tête haute et les genoux légèrement fléchis. Coudes légèrement fléchis. Lever les coudes à la hauteur des épaules. Prise neutre ou marteau.

Sem.	Séries	Rep	Tempo	Charge (kg)	Repos
1-4	2	10 - 12	2-0-2-0		01:30

7 - Debout Barbell Biceps Curl

- Les pieds à la largeur des épaules, faire des flexions de coudes en tenant la barre avec les mains à la largeur des épaules prise supination (paume vers l'avant). Garder les abdos tendus et le dos droit.

Sem.	Séries	Rep	Tempo	Charge (kg)	Repos
1-4	2	10 - 12	2-0-2-0		01:30

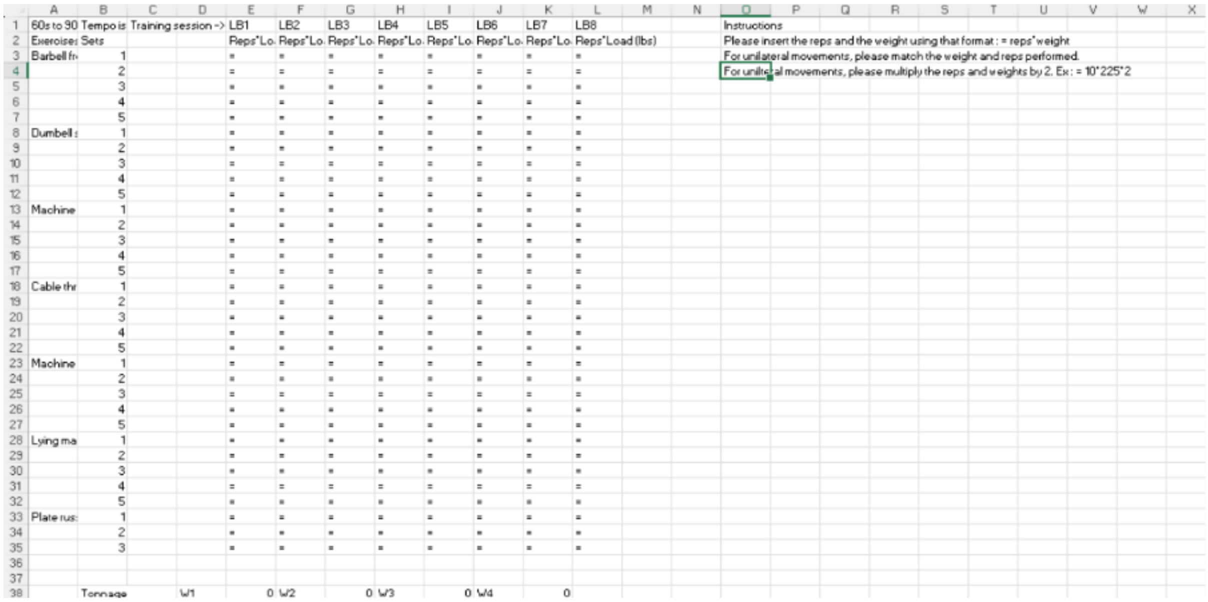
8 - Extension coudes poulie avec corde

- Garder les abdos contractés et le dos droit. Faire des extensions des coudes. Prise neutre avec corde.

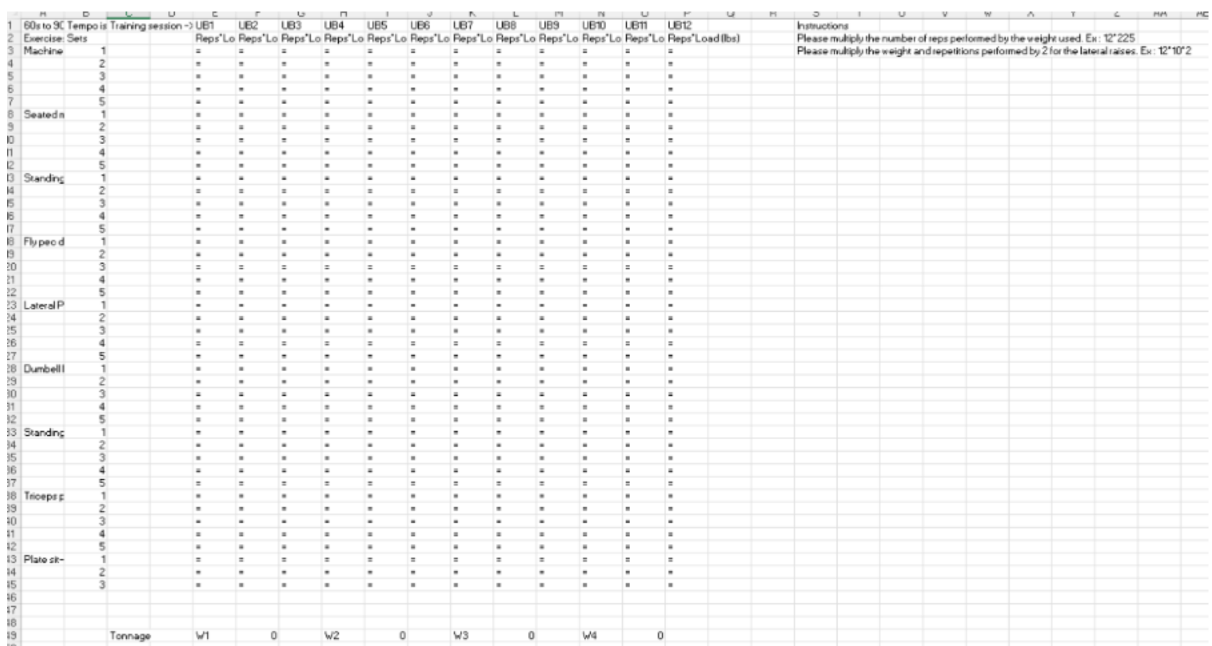
Sem.	Séries	Rep	Tempo	Charge (kg)	Repos
1-4	2	10 - 12	2-0-2-0		01:30

Figure 3. Prescribed training logs used for the lower-body (a) and upper-body (b) programs among HVRT (1) and LVRT (2), respectively.

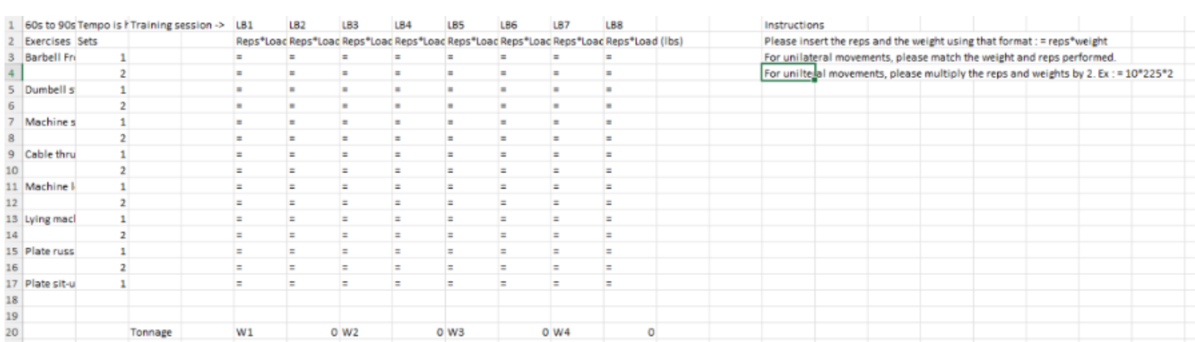
1a.



	A	B	C	D	E	F	G	H	I	J	K	L	O
1	60s to 90	Tempo is	Training session ->		LB1	LB2	LB3	LB4	LB5	LB6	LB7	LB8	Instructions
2	Exercises	Sets			Reps*Lo	Reps*Lo	Reps*Lo	Reps*Lo	Reps*Lo	Reps*Lo	Reps*Lo	Reps*Load (lbs)	Please insert the reps and the weight using that format : = reps*weight
3	Barbell fr	1			=	=	=	=	=	=	=	=	For unilateral movements, please match the weight and reps performed.
4		2			=	=	=	=	=	=	=	=	For unilteral movements, please multiply the reps and weights by 2. Ex : = 10*225*2
5		3			=	=	=	=	=	=	=	=	
6		4			=	=	=	=	=	=	=	=	
7		5			=	=	=	=	=	=	=	=	
8	Dumbell s	1			=	=	=	=	=	=	=	=	
9		2			=	=	=	=	=	=	=	=	
10		3			=	=	=	=	=	=	=	=	
11		4			=	=	=	=	=	=	=	=	
12		5			=	=	=	=	=	=	=	=	
13	Machine	1			=	=	=	=	=	=	=	=	
14		2			=	=	=	=	=	=	=	=	
15		3			=	=	=	=	=	=	=	=	
16		4			=	=	=	=	=	=	=	=	
17		5			=	=	=	=	=	=	=	=	
18	Cable thr	1			=	=	=	=	=	=	=	=	
19		2			=	=	=	=	=	=	=	=	
20		3			=	=	=	=	=	=	=	=	
21		4			=	=	=	=	=	=	=	=	
22		5			=	=	=	=	=	=	=	=	
23	Machine	1			=	=	=	=	=	=	=	=	
24		2			=	=	=	=	=	=	=	=	
25		3			=	=	=	=	=	=	=	=	
26		4			=	=	=	=	=	=	=	=	
27		5			=	=	=	=	=	=	=	=	
28	Lying ma	1			=	=	=	=	=	=	=	=	
29		2			=	=	=	=	=	=	=	=	
30		3			=	=	=	=	=	=	=	=	
31		4			=	=	=	=	=	=	=	=	
32		5			=	=	=	=	=	=	=	=	
33	Plate rus	1			=	=	=	=	=	=	=	=	
34		2			=	=	=	=	=	=	=	=	
35		3			=	=	=	=	=	=	=	=	
36													
37													
38		Tonnage		W1	0	W2	0	W3	0	W4	0		

1b. 

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	S
1	60s to 90	Tempo is	Training session ->		UB1	UB2	UB3	UB4	UB5	UB6	UB7	UB8	UB9	UB10	UB11	UB12	Instructions
2	Exercise:	Sets			Reps*Lo	Reps*Lo	Reps*Lo	Reps*Lo	Reps*Lo	Reps*Lo	Reps*Lo	Reps*Lo	Reps*Lo	Reps*Lo	Reps*Lo	Reps*Load (lbs)	Please multiply the number of reps performed by the weight used. Ex : 12*225
3	Machine	1			=	=	=	=	=	=	=	=	=	=	=	=	Please multiply the weight and repetitions performed by 2 for the lateral raises. Ex : 12*10*2
4		2			=	=	=	=	=	=	=	=	=	=	=	=	
5		3			=	=	=	=	=	=	=	=	=	=	=	=	
6		4			=	=	=	=	=	=	=	=	=	=	=	=	
7		5			=	=	=	=	=	=	=	=	=	=	=	=	
8	Seated m	1			=	=	=	=	=	=	=	=	=	=	=	=	
9		2			=	=	=	=	=	=	=	=	=	=	=	=	
10		3			=	=	=	=	=	=	=	=	=	=	=	=	
11		4			=	=	=	=	=	=	=	=	=	=	=	=	
12		5			=	=	=	=	=	=	=	=	=	=	=	=	
13	Standing	1			=	=	=	=	=	=	=	=	=	=	=	=	
14		2			=	=	=	=	=	=	=	=	=	=	=	=	
15		3			=	=	=	=	=	=	=	=	=	=	=	=	
16		4			=	=	=	=	=	=	=	=	=	=	=	=	
17		5			=	=	=	=	=	=	=	=	=	=	=	=	
18	Fly pec d	1			=	=	=	=	=	=	=	=	=	=	=	=	
19		2			=	=	=	=	=	=	=	=	=	=	=	=	
20		3			=	=	=	=	=	=	=	=	=	=	=	=	
21		4			=	=	=	=	=	=	=	=	=	=	=	=	
22		5			=	=	=	=	=	=	=	=	=	=	=	=	
23	Lateral P	1			=	=	=	=	=	=	=	=	=	=	=	=	
24		2			=	=	=	=	=	=	=	=	=	=	=	=	
25		3			=	=	=	=	=	=	=	=	=	=	=	=	
26		4			=	=	=	=	=	=	=	=	=	=	=	=	
27		5			=	=	=	=	=	=	=	=	=	=	=	=	
28	Dumbell l	1			=	=	=	=	=	=	=	=	=	=	=	=	
29		2			=	=	=	=	=	=	=	=	=	=	=	=	
30		3			=	=	=	=	=	=	=	=	=	=	=	=	
31		4			=	=	=	=	=	=	=	=	=	=	=	=	
32		5			=	=	=	=	=	=	=	=	=	=	=	=	
33	Standing	1			=	=	=	=	=	=	=	=	=	=	=	=	
34		2			=	=	=	=	=	=	=	=	=	=	=	=	
35		3			=	=	=	=	=	=	=	=	=	=	=	=	
36		4			=	=	=	=	=	=	=	=	=	=	=	=	
37		5			=	=	=	=	=	=	=	=	=	=	=	=	
38	Triceps p	1			=	=	=	=	=	=	=	=	=	=	=	=	
39		2			=	=	=	=	=	=	=	=	=	=	=	=	
40		3			=	=	=	=	=	=	=	=	=	=	=	=	
41		4			=	=	=	=	=	=	=	=	=	=	=	=	
42		5			=	=	=	=	=	=	=	=	=	=	=	=	
43	Plate sit-	1			=	=	=	=	=	=	=	=	=	=	=	=	
44		2			=	=	=	=	=	=	=	=	=	=	=	=	
45		3			=	=	=	=	=	=	=	=	=	=	=	=	
46																	
47																	
48																	
49			Tonnage		W1	0	W2	0	W3	0	W4	0					

2a. 

	A	B	C	D	E	F	G	H	I	J	K	L	
1	60s to 90s	Tempo is	Training session ->		LB1	LB2	LB3	LB4	LB5	LB6	LB7	LB8	Instructions
2	Exercises	Sets			Reps*Load	Reps*Load	Reps*Load	Reps*Load	Reps*Load	Reps*Load	Reps*Load	Reps*Load (lbs)	Please insert the reps and the weight using that format : = reps*weight
3	Barbell Fr	1			=	=	=	=	=	=	=	=	For unilateral movements, please match the weight and reps performed.
4		2			=	=	=	=	=	=	=	=	For unilteral movements, please multiply the reps and weights by 2. Ex : = 10*225*2
5	Dumbell s	1			=	=	=	=	=	=	=	=	
6		2			=	=	=	=	=	=	=	=	
7	Machine s	1			=	=	=	=	=	=	=	=	
8		2			=	=	=	=	=	=	=	=	
9	Cable thru	1			=	=	=	=	=	=	=	=	
10		2			=	=	=	=	=	=	=	=	
11	Machine l	1			=	=	=	=	=	=	=	=	
12		2			=	=	=	=	=	=	=	=	
13	Lying macl	1			=	=	=	=	=	=	=	=	
14		2			=	=	=	=	=	=	=	=	
15	Plate russ	1			=	=	=	=	=	=	=	=	
16		2			=	=	=	=	=	=	=	=	
17	Plate sit-u	1			=	=	=	=	=	=	=	=	
18													
19													
20			Tonnage		W1	0	W2	0	W3	0	W4	0	

2b.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	60s to 90s	Tempo is h	Training session ->		UB1	UB2	UB3	UB4	UB5	UB6	UB7	UB8	U9	UB10	UB11	UB2			Instructions
2	Exercises	Sets			Reps*Loac	Reps*Loac	Reps*Loac	Reps*Loac	Reps*Loac	Reps*Loac	Reps*Loac	Reps*Loac	Reps*Loac	Reps*Loac	Reps*Loac	Reps*Load (lbs)			Please multiply the number of reps performed by the weight used. Ex : 12*225
3	Machine c	1			=	=	=	=	=	=	=	=	=	=	=	=			Please multiply the weight and repetitions performed by 2 for the lateral raises. Ex : 12*10*2
4		2			=	=	=	=	=	=	=	=	=	=	=	=			
5	Seated ma	1			=	=	=	=	=	=	=	=	=	=	=	=			
6		2			=	=	=	=	=	=	=	=	=	=	=	=			
7	Standing b	1			=	=	=	=	=	=	=	=	=	=	=	=			
8		2			=	=	=	=	=	=	=	=	=	=	=	=			
9	Fly pec dec	1			=	=	=	=	=	=	=	=	=	=	=	=			
10		2			=	=	=	=	=	=	=	=	=	=	=	=			
11	Lateral Pu	1			=	=	=	=	=	=	=	=	=	=	=	=			
12		2			=	=	=	=	=	=	=	=	=	=	=	=			
13	Dumbell la	1			=	=	=	=	=	=	=	=	=	=	=	=			
14		2			=	=	=	=	=	=	=	=	=	=	=	=			
15	Standing b	1			=	=	=	=	=	=	=	=	=	=	=	=			
16		2			=	=	=	=	=	=	=	=	=	=	=	=			
17	Triceps pu	1			=	=	=	=	=	=	=	=	=	=	=	=			
18		2			=	=	=	=	=	=	=	=	=	=	=	=			
19																			
20																			
21			Tonnage		W1	0		W2	0		W3	0		W4	0				