Muscle typology influences the number of repetitions to failure during resistance training

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Abstract

This study examined whether muscle typology (muscle fiber type composition) is related to maximal strength and whether it can explain the high inter-individual variability in number of repetitions to failure during resistance training. Ninety-five resistance training novices (57 males) were assessed for their maximal isometric knee extension strength and muscle typology. Muscle typology was estimated by measuring carnosine in the soleus, gastrocnemius and/or vastus lateralis using proton magnetic resonance spectroscopy. Forty-four subjects (22 males) performed dynamic strength tests (1RM) and 3 sets of leg extensions and curls to failure (60%1RM) to determine the association between muscle typology and (total) number of repetitions. Twenty-one subjects performed additional biceps curls and triceps extensions (60%1RM) to assess influence of exercise, 23 subjects performed additional leg extensions and curls at 80% and 40%1RM to evaluate influence of training load. There was a weak but significant relationship between muscle typology and maximal isometric strength ($r=0.22$, $p=0.03$) favoring the fast typology individuals. Slow and fast typology individuals did not differ in upper arm and upper leg 1RM. Total number of repetitions was related to muscle typology at 80% ($r=-0.42$; $p=0.04$) and 60% ($p=-0.44$; $p=0.003$) but not at 40%1RM. Slow typology individuals performed more repetitions to failure at 60%1RM in the leg extension ($p=0.03$), leg curl ($p=0.01$) and biceps curl ($p=0.02$). In conclusion, muscle typology has a small contribution to maximal isometric strength but not dynamic strength and partly determines the number of repetitions to failure during resistance training. This insight can help individualizing resistance training prescriptions.

Highlights:

- Having a fast muscle typology is positively associated with maximal isometric strength delivery in resistance training novices.
- The muscle typology seems to be a determining characteristic in the number of repetitions that can be performed during resistance training as slow typology individuals perform significantly more repetitions to failure compared to fast typology individuals.
- This study indicates the importance for coaches to shift from using traditional load-repetition tables and 1RM prediction equations to individualized 1RM testing and training volume prescriptions.

Keywords: Musculoskeletal, physiology, resistance, strength

Introduction

Resistance training is a valuable strategy to reduce the risk to develop chronic diseases, to improve overall health and to optimize athletic performance[1]. A correct manipulation of the resistance training variables is required to optimize an individual's strength and hypertrophy. Two of these important variables are the training load and volume. Load is typically expressed as a percentage of maximal strength (e.g. percentage of one-repetition maximum (%1RM)) whereas volume is often expressed as the total number of repetitions performed per exercise[2].

Large inter-individual variations exist in the number of repetitions performed to failure at a given percentage of 1RM for a given exercise[3]. However, coaches still determine the number of repetitions their athletes need to execute based on traditional "non-exercise specific load-repetition relationship" tables[4]. Moreover, they estimate the 1RM based on the number of repetitions performed at a submaximal load using prediction equations[5]. These tables and equations - that do not take into account personal characteristics - may lead to inadequate prescriptions and suboptimal training stimuli[6,7]. It is thus clear that the need to individualize the number of repetitions per athlete arises instead of sticking to the "one-fits-all" training principle.

Muscle typology might be a missing key factor in understanding this high inter-individual variability in number of repetitions. Human skeletal muscles are composed of a mixture of slow-twitch fibers (type I) and fast-twitch fibers (type IIa and IIx). This fiber type distribution shows a high inter-individual variation ranging from 15% to 85% fast-twitch fibers[8] and can characterize people as dominant slow typology individuals (ST), intermediate typology individuals (IT) or fast typology individuals (FT). Slow-twitch fibers are inherently more fatigue resistant[9] while fast-twitch fibers can generate more power[10]. These fiber characteristics have been shown to reflect themselves in sports practice. In 2011, a non-invasive alternative to measure muscle typology has been developed based on the measurement of muscle carnosine with proton magnetic resonance spectroscopy (^{1}H-MRS)[11]. Fast-twitch fibers have a 1.7 to 2.2 times higher carnosine concentration compared to slow-twitch fibers[12,13] and positive correlation between the percentage area occupied by fast-twitch fibers and the muscle carnosine concentration ($r = 0.71$, $p = 0.009$) has been demonstrated[11]. With this approach, it was demonstrated that FT individuals fatigue more and need longer recovery compared to ST individuals after high-intensity exercise[14]. Validity of the technique was further confirmed in elite athletes excelling in respectively sprint and endurance events in track-and-field and cycling[11,15]. As this technique allows for investigating of muscle typology in large sample sizes, it will therefore be used in this study.

Over the last twenty years, a small amount of research has been conducted regarding the role of muscle typology in number of repetitions with equivocal results. Some studies found an inverse relationship between the number of repetitions and the fast-twitch fiber percentage[16–18] while this could not be reproduced by Terzis et al.[19] or Hickson et al.[18] at high loads (≥70%). Importantly, except for the small-sample study of Hickson[18], all before mentioned studies[16,17,19] only focused on quadriceps targeting exercises at high loads and on the first set of exercise. Further research is needed since a) the number of repetitions can differ depending on the exercise (e.g. biceps or leg curl[3]), b) inter-individual ranges in the number of repetitions are greater at lower loads[3] and c) it is important to take the total training volume into account as this will be more determining for training outcomes than the training volume of the first set only[20].

In order to understand whether the number of repetitions at a certain percentage of 1RM is influenced by muscle typology, one needs to consider that dynamic (1RM) and maximal isometric strength itself are possibly already different between ST and FT individuals. This is still unclassified in the literature and will be explored in the first aim of this study in a large cohort of male and female resistance training novices. Secondly, we aim to investigate the relationship between the total number of repetitions performed during a training session and the ^{1}H-MRS-derived muscle typology. We will also explore whether this relationship is dependent on the exercise type and on training load. We hypothesized that resistance training novices with a fast muscle typology will display higher maximal dynamic and isometric strength and will perform less repetitions at all exercises and intensities.

Materials and methods

More details about the subjects, materials and methods can be found in the Supplementary Materials and Methods (SM).

Subjects

Ninety-five resistance training novices (57 males, 38 females) participated in this cross-sectional study. Their average age, body mass and height were respectively 23.4 ± 2.6 years, 72.7 ± 7.0 kg and 1.80 ± 0.06 m (males) and 23.6 ± 2.4 years, 65.1 ± 9.0 kg and 1.68 ± 0.07 m (females). Subjects gave written informed consent, the study was conducted according to the Declaration of Helsinki and was approved by the local ethics committee (Ghent University Hospital, Belgium). More details in SM.

Study design

Muscle typology and maximal isometric knee extension strength were determined in all 95 subjects to investigate the relationship between both. To assess the relationship between muscle typology and total number of repetitions during resistance training, 44 subjects (repetition group) performed further maximal dynamic strength tests and 3 sets of leg extensions and curls to failure (60% 1RM). Subjects were selected based on their pronounced slow or fast muscle typology: 21 ST individuals (11 males), 21 FT individuals (10 males) and 2 subjects with an intermediate muscle typology (IT, 1 male). To investigate possible influence of exercise or training load on the relationship between muscle typology and number of repetitions, the 44 subjects were further divided into two subgroups: an exercise (n = 21) and a load group (n = 23). The exercise group (11 ST (6 males), 10 FT (5 males)) performed additional biceps curls and triceps extensions at 60% 1RM to failure. The load group (10 ST (5 males), 11 FT (5 males), 2 IT) performed additional leg extensions and curls at 80% and 40% 1RM (Figure S1). Additionally, soleus, gastrocnemius and vastus lateralis carnosine concentrations were measured in a group of 43 recreationally active subjects (28 males, mean age: 25.0 ± 4.2yrs) to investigate the inter-muscular carnosine relationship.

Muscle typology

Muscle carnosine content was measured by proton magnetic resonance spectroscopy (^{1}H-MRS) in the right soleus and gastrocnemius of all 95 subjects to estimate muscle typology[11]. At the start of the repetition analysis, also vastus lateralis carnosine content could be reliably measured and therefore additional vastus lateralis carnosine measurements were performed in the repetition group (n = 44) and the inter-muscular carnosine relation group (n = 43). Due to methodological (low-quality hamstring spectra, possibly due to large amounts of connective tissue, and the non-existence of a reference database in the biceps and triceps) and time constraints (subjects would need to lay under the MRI scanner for 1.5h to investigate all trained muscles), the muscle typology could not be measured in all trained muscles. Therefore, the muscle typology of the soleus, gastrocnemius and vastus lateralis is a rough estimate of the muscle typology of the biceps, triceps and hamstring muscles. All ^{1}H-MRS measurements were performed on a 3T whole body magnetic resonance imaging scanner (Siemens, Healthineers AG, Erlangen) as previously described[21]. Measurements were performed in the part of the muscles containing the largest muscle mass, to avoid incorporation of muscle fascia and subcutaneous fat[21]. The carnosine concentration of each muscle was converted to a z-score relative to an age- and gender-matched control population of active, healthy non-athletes (soleus and gastrocnemius: 163 males, 112 females; vastus lateralis: 70 males, 56 females). The mean of the carnosine z-scores of the soleus and gastrocnemius was calculated and used in the isometric strength analyses. For the repetition analyses, the mean of the carnosine z-scores of all scanned muscles was calculated. The subjects were divided into 3 groups based on their z-score: ST individuals (z-score ≤ -0.5), intermediate individuals (z-score between −0.5 and +0.5) and FT individuals (z-score ≥ +0.5). IT individuals are included in all analyses except the ANOVAs.

Anthropometry

Body mass was measured using a digital scale (0.1 kg, Tanita BC-420SMA) and height with a portable stadiometer (0.1 cm, Seca 213 Portable). In the repetition group, upper leg fat free mass (ULFFM) of the right leg was estimated based on anthropometric measurements as described by Layec et al[22].

Maximal strength

Peak isometric knee extension torque of the right leg was assessed using a dynamometer (System 3 pro; Biodex medical system). Subjects performed two 5 seconds Maximal Voluntary Contractions (MVC) interspersed with two minutes of rest. Subjects were seated with a knee angle of 90° and extraneous movements were limited by two shoulder straps and by crossing the arms in front of the body. More details in SM.

Maximal dynamic strength was determined as the maximal weight the subjects could lift unilateral in one-repetition (1RM) over a full range of motion with proper technique as previously described[4] for 4 different exercises: seated leg extension and seated leg curl

(Technogym, Selection 900), standing biceps curl and lying triceps extension (dumbbell weights). More details in SM.

Repetition to Failure Protocol

Forty-four subjects performed leg extensions and curls to failure at 60% 1RM. On the same day, the exercise group (n=21) performed additional biceps curls and triceps extensions at 60% 1RM to failure in random order. The load group (n=23) performed two extra test days (separated by ≥ 48 hours) with leg extensions and leg curls to failure at 80% and 40% 1RM. On a test day, participants performed a 5 minutes warming-up on a rowing or cycling ergometer followed by an exercise specific warming-up of 2x10 repetitions at 20% 1RM. Thereafter, 3 sets to failure (the inability to perform another repetition over the full range of motion or with proper technique) were performed per exercise with 1s concentric and 2s eccentric contractions and respectively 2 and 3 minutes recovery between sets and exercises. Day-to-day variability in total number of repetitions was on average 10.27%.

Statistical analysis

The highest registered torque from the two MVCs was selected as the peak isometric knee extension torque and calculated relative to the participants' body mass (Nm/kg BM). For dynamic strength, 1RM was also calculated relative to body mass (kg/ kg BM). To account for gender differences in peak isometric torque, maximal dynamic strength and number of repetitions, gender specific z-scores were made for these variables. These z-scores were used to be able to include both genders in the same correlation analysis. Covariates for gender were used when including both genders in the same ANOVA.

Shapiro-Wilk's tests were used to control for normality of the data. Pearson correlations were conducted to reveal inter-muscular carnosine relationships and relationships between muscle typology and maximal isometric torque, maximal dynamic strength and (total) number of repetitions. If data were skewed, Spearman rank correlations were used. Two-way repeated measures ANCOVAs (set x muscle typology) were used to discover differences in within-training fatigue between ST and FT subjects. Simple main effects analyses with Bonferroni correction were performed to assess influence of muscle typology on within-set fatigue. All statistical analyses were performed using Graphpad Prism (Version 9.3.1; GraphPad Software) and SPPS (SPSS 28.0), 95% confidence intervals (CI) are shown and statistical significance was accepted as $p \leq 0.05$.

Results

Inter-muscular carnosine relationship

The muscle carnosine content correlated significantly between the soleus, gastrocnemius and vastus lateralis, indicating good similarities in muscle typology between different leg muscles (Soleus - Gastrocnemius: n = 87, r = 0.80, p < 0.0001, CI = 0.70 to 0.86; Gastrocnemius - Vastus Lateralis: n = 85, r = 0.74, p < 0.0001, CI = 0.62 to 0.82; Soleus - Vastus Lateralis: n = 85, r = 0.69, p < 0.0001, CI = 0.56 to 0.79) (Figure S2).

Muscle typology and isometric strength

There was a weak, but significant correlation between the subject's mean carnosine z-score and relative peak isometric knee extension torque (Nm/kg; r = 0.22, p = 0.03, CI = 0.02 to 0.40; Figure 1A). This cautiously indicates that FT individuals can generate a higher relative knee extension peak torque. When analyzing the data separately for both genders, only the males showed a significant relationship (Males: r = 0.26, p = 0.05, CI = -0.008 to 0.49; Females: r = 0.16, p = 0.35, CI = -0.17 to 0.45; Figure 1B). Similar relationships were found between mean carnosine z-score and absolute peak isometric knee extension torque (Nm; all: r = 0.30, p = 0.003, CI: 0.11 to 0.47; men: r = 0.37, p = 0.01, CI: 0.12 to 0.58; women: r = 0.19, p = 0.24, CI: -0.13 to 0.48)

Muscle typology and number of repetitions

A high heterogeneity in the number of repetitions per set and per exercise existed in all exercises and at all training loads. Depending on the exercise and the load a two- to fourfold inter-individual difference was found between the lowest and highest number of repetitions (Table 1).

There was a significant negative relationship between the mean carnosine z-score and total number of repetitions during a resistance training with 3 sets of leg extensions and 3 sets of leg curls to failure at 60% 1RM (r = -0.44, p = 0.003, CI: -0.65 to -0.16) (Figure 2A and 2B). These results indicate that FT individuals reach failure after a lower number of repetitions. This could not be explained by the subject's ULFFM or 1RM as there was no difference between ST and FT individuals for their ULFFM (6711.43 ± 1406.30 cm^3 (ST) vs 6548.11 ± 994.80 cm^3 (FT), p = 0.62), relative leg extension 1RM (0.71 ± 0.11 kg/kg BM (ST) vs 0.71 ± 0.11 kg/kg BM (FT), p = 0.75) and leg curl 1RM (0.52 ± 0.09 kg/kg BM (ST) vs 0.52 ± 0.15 kg/kg BM (FT), p = 0.82). Moreover, a significant main effect of muscle typology revealed that the number of repetitions is on average higher per set in ST individuals compared to FT individuals for both the leg extension ($p = 0.03$) and leg curl ($p = 0.01$), indicating a higher-within set fatigue in FT individuals (Figure 2C and 2D). It could be hypothesized that the difference in number of repetitions becomes even more pronounced in set 2 and set 3 when fatigue accumulates. However, for both exercises, there were no significant interaction effects (set x muscle typology) indicating similar within-training fatigue patterns between ST and FT individuals.

For the arm exercises, there was a significant main effect of muscle typology for biceps curl ($p = 0.02$) but not for triceps extension ($p = 0.96$) (Figure 2E and 2F). Comparable to the leg exercises, there were no significant interaction effects indicating similar within-training fatigue for ST and FT subjects for both the biceps curl and triceps extension. Again, there were no differences in relative biceps curl (0.20 ± 0.07 kg/kg BM (ST) vs 0.22 ± 0.05 kg/kg BM (FT), $p = 0.06$) and triceps extension 1RM (0.12 ± 0.04 kg/kg BM (ST) vs 0.13 ± 0.05 kg/kg BM (FT), $p = 0.21$) between both typologies.

Regarding the influence of training load, there was a significant negative correlation between the mean carnosine z-score and total number of repetitions per training at 80% ($r = -0.42$, $p = 0.04$, CI: -0.71 to -0.01) and 60% 1RM ($r = -0.41$, $p = 0.05$, CI: -0.70 to 0.002) but not at 40% 1RM ($r = -0.23$, $p = 0.28$, CI: -0.60 to 0.18) (Figure 3). Total number of repetitions (3 sets of leg extensions and 3 sets of leg curls) ranged from 30 to 60 at 80% 1RM, 63 to 122 at 60% 1RM and 123 to 410 at 40% 1RM. No significant relationships were found between the mean carnosine z-score and the total number of repetitions per exercise.

Discussion

In this study we explored whether the wide diversity in muscle typology can explain some of the heterogeneity observed in maximal muscle strength and in the number of repetitions to failure in resistance training novices. We found a weak association with maximal isometric, but not dynamic strength. However, a stronger association was found with number of repetitions.

Thanks to our large study sample, this study demonstrates a small contribution of the muscle typology to the maximal isometric knee extension strength.. The positive correlation between the carnosine z-score and peak isometric knee extension strength indicates a somewhat higher maximal isometric torque in FT individuals. Yet, the explained variance was a mere 5%. Additionally, the finding was only corroborated in men and was not observed in women. Given the importance of fiber CSA[23] in isometric strength this might be because in females the CSA of slow-twitch fibers is of similar size or bigger than fast-twitch fibers while the fast-twitch fibers of males have an 8-15% higher CSA[8]. Therefore, the effect of a higher fast-twitch fiber percentage might be beneficial for maximal strength delivery in males but not in females. Until now, the influence of muscle typology on isometric strength was debated and only studied in relatively small sample sizes. Some studies found strong relationships between the fast-twitch fiber percentage and peak isometric strength. However, most of these studies like Methenitis et al.[24] included individuals with and without resistance training experience in the same analysis making it difficult to draw conclusions. Tesch et al.[25] took this into account by only including male resistance training novices and found moderate correlations between fast-twitch fiber percentage and peak isometric strength (r=0.46). However, in a direct comparison of single fiber contractility of human muscles, most studies show no differences in the peak isometric force between slow and fast muscle fibers when normalized for fiber cross-sectional area (CSA)[23]. The influence of muscle typology on dynamic strength has been less investigated. We found no differences in 1RM between ST and FT individuals in the 4 exercises. This is in agreement with previous data in untrained women[16]. Taken together, the diversity in muscle typology is only a minor but real factor in the heterogeneity in maximal isometric muscle strength and this role is probably even smaller for dynamic strength, at least for the relatively slow contraction modes applied here.

A more consistent observation in our study was the relationship between muscle typology and number of repetitions to failure. ST individuals performed a substantially higher total number of repetitions compared to FT individuals at 60% and 80% 1RM. This is in agreement with the findings of previous research demonstrating inverse relationships between the number of repetitions in set 1 and the fast-twitch percentage at intensities of 80% and 70% in quadriceps targeting exercises[16,17]. Our study shows for the first time in a large cohort that these results are also applicable for total training volume, at moderate loads and in the biceps and hamstring muscle. We revealed a lower number of repetitions in FT individuals in most of the sets indicating a higher within-set fatigue. This is in line with the findings of Colliander et al. (1988) who found a positive relationship between the fast-twitch area and the decrease in within-set peak torque[26]. Fast-twitch fibers rely more on the glycolytic energy delivery system[27] and the cross-bridges of fast-twitch fibers have a faster consumption of ATP[28]. This possibly leads to the faster accumulation of metabolic by-products followed by an earlier onset of peripheral within-set fatigue and contraction failure[29]. Despite differences in within-set fatigue, the within-training fatigue was similar for ST and FT individuals indicating a similar fatigue accumulation over the sets. This is in contrast to previous results demonstrating impaired torque recovery in the FT individuals after set 1 (FT: 82% vs ST: 93%) and set 2 (FT: 72% vs ST: 89%)[26].

Noteworthy, the number of repetitions differed between ST and FT individuals in the leg extension, leg curl and biceps curl, but not in the triceps extension. Of the investigated muscles, the triceps brachii is the muscle with the highest fast-twitch fiber proportion[30]. Moreover, it is a non-postural muscle not involved in many daily activities and all subjects were novices not used to perform this specific movement. Therefore, performing triceps extensions may have caused faster and substantial fatigue accumulation in all subjects which is indeed reflected in a higher drop in number of repetitions from set 1 to set 2 (TE: -50%) compared to the other exercises (LE: -18%; LC: -28%; BC: -38%). Lastly, it might be possible that the muscle typology in the triceps differs from the ^{1}H-MRS derived typology in the leg muscles. However, further research is needed to clarify this.

Although training at lower loads of 40% induces more metabolic fatigue[31], no significant relationship was found between muscle typology and the total number of repetitions at 40% 1RM. This is in contrast with previous research[18] demonstrating a positive relationship (r=0.69) with the slow-twitch percentage, albeit in only 8 subjects. The absence of this relationship might be related to the inter-individual difference in ‘critical load’ for dynamic exercises. This is the highest sustainable resistance that can be completed for an extended number of repetitions and separates two intensity zones with different fatigue mechanisms[32]. The critical load is variable per individual and based on the few performed studies ranges between 25% (leg extension) and 50% 1RM depending on the exercise type[32]. As no data are available for the leg curl yet, for some subjects 40% might have been below their critical load which possibly caused a delay in their fatigue accumulation and is reflected in some individuals completing several hundreds of repetitions.

The observation that muscle typology considerably influences the number of repetitions during resistance training indicates that the load-repetition relationship tables mostly fail at the individual level. This study suggests that a lower number of repetitions should be prescribed to FT individuals at the same %1RM as ST individuals. Conversely, the estimation of 1RM from the number of repetitions at submaximal loads is equally impacted by muscle typology variation. Take the example of two individuals both having a true leg curl 1RM of 34 kg. If they – based on the range in leg curl repetitions – respectively perform 14 (a ST individual) and 5 (a FT individual) repetitions at 27 kg (80% 1RM) then their estimated 1RM based on the traditional tables and guidelines would be 42 kg and 31 kg, respectively. So if one only derives the 1RM from the tables and equations, the 1RM might be underestimated in the FT individuals and overestimated in the ST individuals. These findings will help coaches to understand the importance of individualized training prescriptions. This can be performed by multiple RM tests per athlete (1RM, 8RM,…) or non-invasively estimating the muscle typology.

We acknowledge that the muscle typology in the isometric knee extension strength cohort (n = 95) was only measured in the soleus and gastrocnemius. However, the good correlations found between soleus, gastrocnemius and vastus lateralis carnosine concentrations in this study indicate that using the carnosine z-score of the soleus and gastrocnemius was a valid alternative to estimate muscle typology in the vastus lateralis. Following this pattern, one could also assume that the muscle typology in the leg muscles can predict the muscle typology in the arm muscles. The across-muscle phenotype as described by Vikne et al., (2012)[33] and data from our own group[34], demonstrating significant correlations between the deltoideus muscle and gastrocnemius in an athlete population ($r = 0.81$, $p < 0.01$) and control population ($r = 0.37$, $p < 0.05$), provide some evidence for this. However, since we did not measure the muscle typology in the biceps or triceps due to methodological reasons, we want to emphasize that this remains a rough estimate that we cannot fully substantiate.

Conclusion

The present study suggests a small influence of muscle typology on isometric strength but not on dynamic strength in resistance training novices. Interestingly, muscle typology seems to be a determining characteristic in the number of repetitions that can be performed per individual as FT individuals perform significantly less repetitions to failure during leg extensions, leg curls and biceps curls at 60% and 80% of 1RM. Consequently, this study indicates the importance of shifting from using traditional tables to individualized testing and training prescriptions.

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Declaration of interest statement

The authors report there are no competing interests to declare.

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Appendices

Supplementary Materials and Methods

Supplementary Figure S1: Flowchart of study design

Supplementary Figure S2: Inter-muscular carnosine relationship between the soleus, gastrocnemius and vastus lateralis. Panel A represents the relationship between the soleus and gastrocnemius, panel B the relationship between the gastrocnemius and vastus lateralis and panel C the relationship between the soleus and vastus lateralis.

Tables

Table 1: Overview of number of repetitions in set 1 and total number of repetitions per exercise (3 sets) for leg extension, leg curl, biceps curl and triceps extension at different loads.

		80% 1RM		**60% 1RM**		**40% 1RM**	
		Mean ± SD	**Range**	**Mean ± SD**	**Range**	**Mean ± SD**	**Range**
Leg extension	**Set 1**	8 ± 2	5 – 12	14 ± 3	9 – 20	28 ± 5	20 – 39
	Total	21 ± 5	11 – 30	36 ± 7	25 – 50	66 ± 11	47 – 90
Leg curl	**Set 1**	9 ± 2	5 – 14	21 ± 4	13 – 32	73 ± 35	33 – 143
	Total	22 ± 5	14 - 33	51 ± 11	26 – 75	173 ± 87	71 – 344
Biceps curl	**Set 1**			16 ± 7	8 – 36		
	Total			34 ± 12	18 – 62		
Triceps extension	**Set 1**			23 ± 7	14 – 37		
	Total			44 ± 16	23 – 79		

Ranges are presented as the minimal and maximal individual performance per exercise and per load.

Figure captions

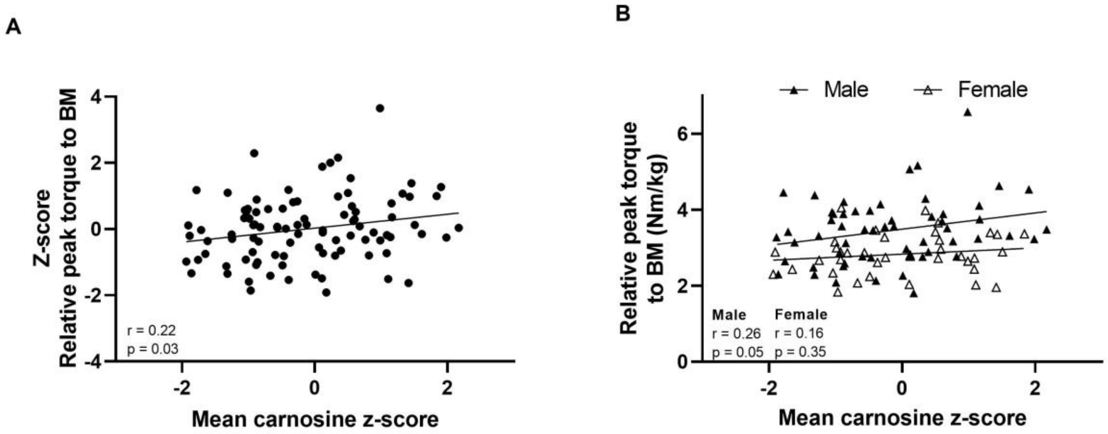


Figure 1: Relationship between mean carnosine z-score and peak isometric knee extension torque expressed as z-scores for (A) all participants and expressed as absolute values for (B) men and women. BM = Body mass

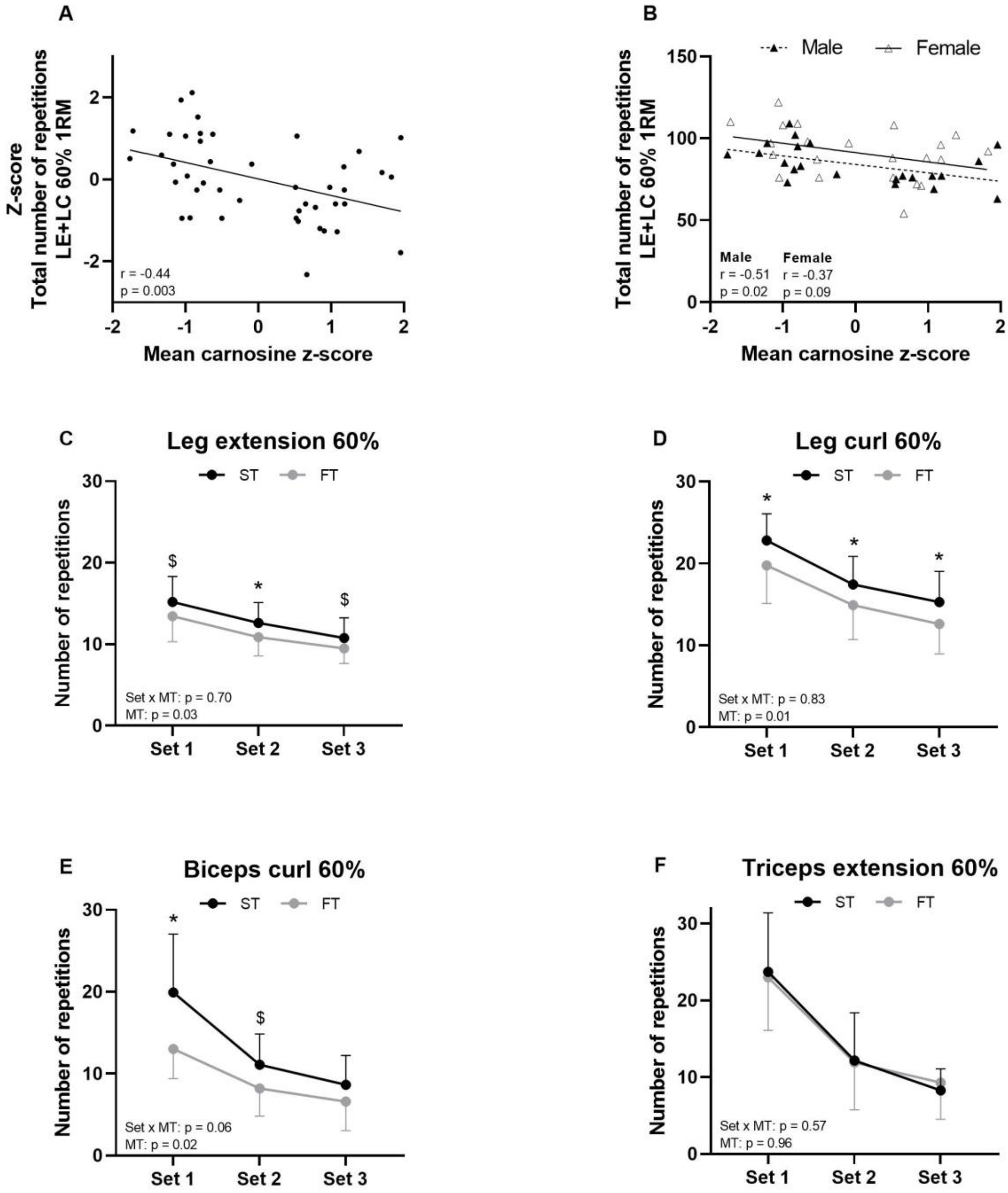


Figure 2: A-B) Relationship between mean carnosine z-score and total number of repetitions in (A) all participants expressed as z-scores or in (B) men and women expressed as absolute values during a training with 3 sets of leg extensions and 3 sets of leg curls at 60% 1RM. C-F) Differences in within-training fatigue (Set x MT) and within-set fatigue (MT) between ST and FT individuals for (C) leg extension, (D) leg curl, (E) biceps curl and (F) triceps extension at 60% 1RM. MT = Main effect of muscle typology; LE = leg extension, LC = leg curl; $*p \leq 0.05$, $^{\$}p \leq 0.1$

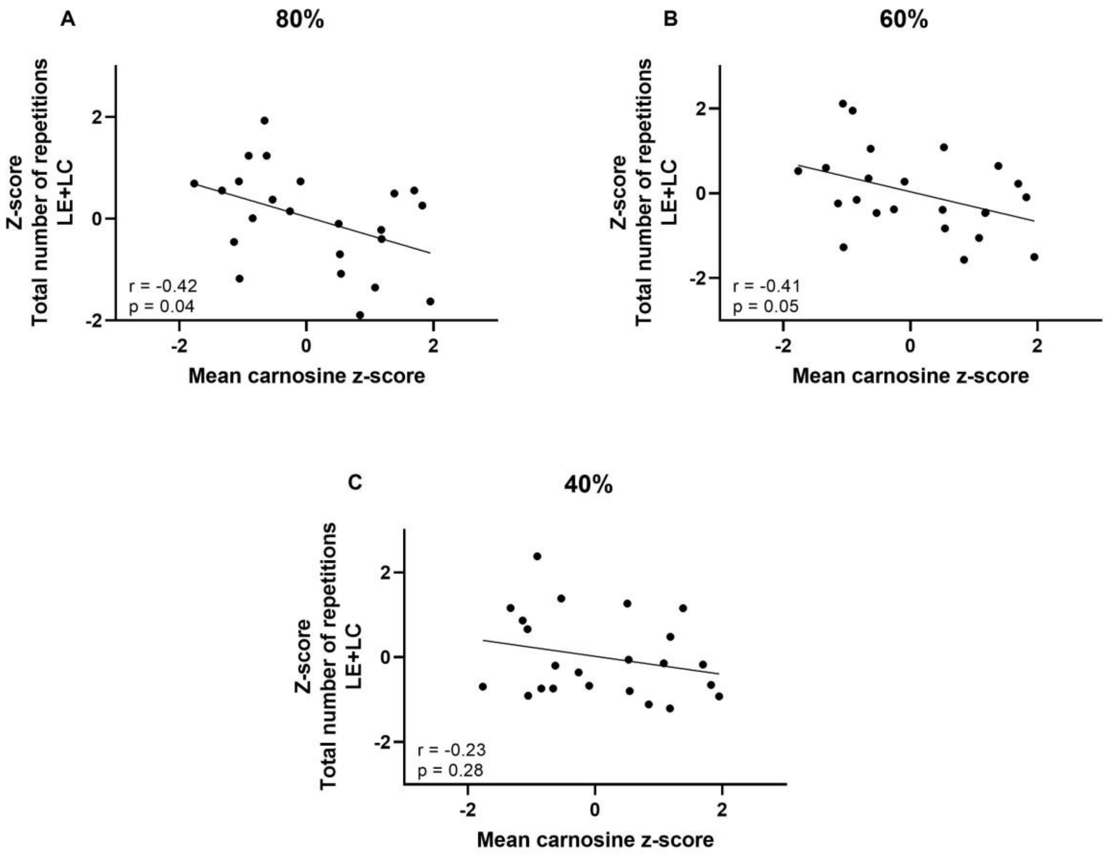
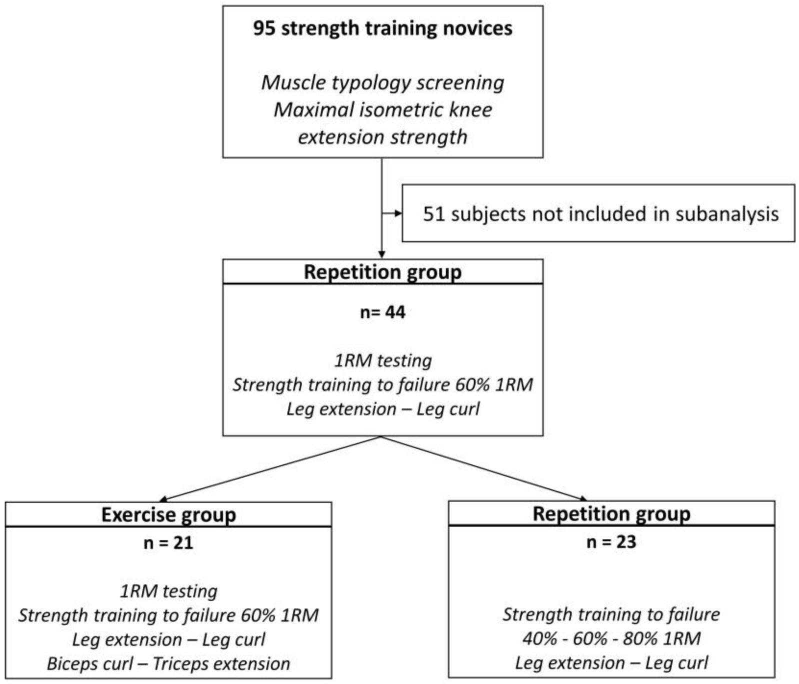
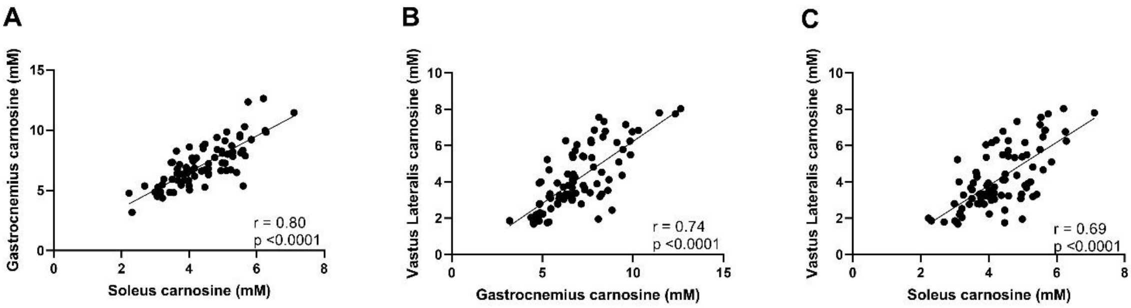


Figure 3: Relationship between mean carnosine z-score and total number of repetitions (expressed as z-scores) during a training with 3 sets of leg extensions and 3 sets of leg curls at (A) 80% 1RM, (B) 60% 1RM and (C) 40% 1RM



Supplementary Figure S1. Study design.



Supplementary Figure S2**.** Inter-muscular carnosine relationship between the soleus, gastrocnemius and vastus lateralis. Panel A represents the relationship between the soleus and gastrocnemius, panel B the relationship between the gastrocnemius and vastus lateralis and panel C the relationship between the soleus and vastus lateralis.