The dose-response of the nordic hamstring exercise on biceps femoris architecture and eccentric knee flexor strength : A randomized interventional trial

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Title

The dose-response of the Nordic hamstring exercise on biceps femoris architecture and eccentric knee flexor strength

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ABSTRACT

Purpose: To examine the dose-response of the Nordic hamstring exercise (NHE) on biceps femoris long head (BFlh) architecture and eccentric knee flexor strength.

Design: Randomized interventional trial.

Methods: Forty recreationally active males completed a six-week NHE training program consisting of either intermittent low volumes (Group 1; n = 10), low volumes (Group 2; n = 10), initial high volumes followed by low volumes (Group 3; n = 10), or progressively increasing volumes (Group 4; n = 10). A four-week de-training period followed each program. Muscle architecture was assessed weekly during training and after two and four weeks of de-training. Eccentric knee flexor strength was assessed pre- and post-intervention and after two and four weeks of de-training.

Results: Following six weeks of training, BFlh fascicle length (FL) increased in Group 3 (mean difference = 0.83 cm, d = 0.45, p = 0.027, +7%) and Group 4 (mean difference = 1.48 cm, d =

0.94, p = 0.004, +14%). FL returned to baseline following detraining in Groups 3 and 4. Strength increased in Group 2 (mean difference 53.6 N, d = 0.55, p = 0.002, +14%), Group 3 (mean difference = 63.4 N, d = 0.72, p = 0.027, +17%), and Group 4 (mean difference = 74.7, d = 0.83, p = 0.006, +19%) following training. Strength returned to baseline following detraining in Groups 2 and 3 but not Group 4.

Conclusions: Initial high volumes of the NHE followed by lower volumes, as well as progressively increasing volumes, can elicit increases in BFlh FL and eccentric knee flexor strength. Low volumes of the NHE was insufficient to increase FL, although, as few as 48 repetitions in six weeks did increase strength.

Key words: eccentric training; fascicle length; muscle architecture; hamstring; ultrasound.

INTRODUCTION

Hamstring strain injuries (HSIs) are the primary injury sustained by soccer players across Europe,[1] with the biceps femoris long head (BFlh) the most commonly injured of the hamstring muscles.[2] HSIs have been estimated to cost €500,000 per month in elite soccer.[1] Therefore, prevention of these injuries remains a central objective in sports medicine.

The Nordic hamstring exercise (NHE) is effective in reducing the incidence of HSI,[3-6] reducing HSI risk by over 50% across multiple sports.[3,6] Additionally, the NHE alters muscle architecture by increasing BFlh fascicle length (FL) and enhances muscle function by increasing eccentric knee flexor strength.[7-9] Short fascicles of BFlh and lower eccentric knee flexor strength are modifiable risk factors for HSI,[2] and may be important considerations for HSI risk mitigation.

Despite the benefits of the NHE for reducing HSI,[6] the occurrence of HSIs appear to be unabated in European soccer.[1] One explanation for these increased HSI rates is poor adherence to the NHE protocol, with the suggestion that high dosages of the exercise may contribute to low compliance.[10] Dosage of the successful HSI prevention protocol has involved up to 90 repetitions per week, totaling over 700 repetitions in 10-weeks.[4] As the NHE involves eccentric overload of the hamstring muscles, delayed onset muscle soreness can be consequential[7] and associated discomfort may result in reduced compliance.[11] Poor compliance to NHE protocols reduces the efficacy,[12] therefore the causes of non-compliance, such as high training volumes, need to be addressed.

Lower exercise dosages of the NHE, in isolation[8, 9] and in combination with modified stiff leg deadlifts,[13] are effective at increasing BFlh FL and eccentric knee flexor strength, with further support for lower dosages from a recent systematic review and meta-analysis.[11] However, the lowest possible prescription of the NHE to achieve positive adaptations in BFlh FL and eccentric strength remains unknown. A minimal effective NHE dose may be useful for practitioners to enhance adherence and to improve time efficiency in injury prevention or strength protocols.[11, 13] Therefore, this study aimed to examine the dose-response of NHE exposure on BFlh fascicle length and eccentric knee flexor strength between groups exposed to different volumes of the NHE.

METHODS

Participants

Forty recreationally active males (32.0 ± 4.3yrs, 180.0 ± 6.6cm, 82.5 ± 9.5kg) were recruited for this study (Figure 1). Participants were recruited from within The Aspire Zone in Doha, Qatar through email communication and word of mouth. All participants provided written informed consent prior to participation in the study, which was approved by the Anti-Doping

Laboratory of Qatar (approval number: F2016000160). Inclusion criteria consisted of healthy, active males, aged between 18 and 40 years of age. Exclusion criteria consisted of a history of HSI or significant lower limb injury in the last year (e.g. ACL rupture, fracture). Participants were advised not to undertake any unaccustomed/strenuous physical activity for 24 hours prior to their laboratory visits.

Study design

This randomized, interventional training study was conducted between March 2018 and January 2019 in Aspetar Orthopaedic and Sports Medicine Hospital, Doha, Qatar. On their first visit, participants were familiarized with the NHE. Following familiarization, participants were randomized to one of four different groups to undertake 6 weeks of NHE training. Initial testing consisted of ultrasound assessment of BFlh architecture and NHE strength assessed during the NHE. Following this assessment, participants commenced their first training session of the intervention. Muscle architecture was re-assessed weekly.

Following intervention completion, participants completed a post-test assessment of BFlh architecture and NHE strength test. Consequently, participants commenced a four-week detraining period. Following two weeks and four weeks of the detraining period participants had both their BFlh architecture and NHE strength re-assessed.

NHE training intervention

All NHE training and testing was completed on a commercially available testing device (Nordbord, Vald Performance, QLD, Australia). This device has been shown to be reliable, with intraclass correlation coefficients of 0.83-0.90 and typical error as a coefficient of variation of 5.8-8.5%.[14] Methods were similar to those described previously.[7-9] Briefly, participants knelt on a padded board, with their arms across their chest (or holding a weight centered to the sternum) and hips extended, participants were instructed to lean forward, lower their body as slowly as possible, and slow their descent as much and as far through range as possible. Participants were instructed to continue to resist maximally until they reached the floor.[9] When participants developed enough strength to stop their movement in the final 10-20° of the range of motion, they were required to hold a weight plate to their chest to ensure the exercise maintained its intensity (weight range: 5-20 kg).[8,9] During all testing and training sessions, participants received strong verbal encouragement to ensure maximal effort for each repetition. Strength data was recorded during all testing sessions in Newtons (N).

Participants completed a training protocol of up to 30 supervised exercise sessions (0 to 3 sessions per week depending on randomization) over the 6-week training period (Table 1). Training sessions were recorded via cloud technology and subsequently downloaded. This facilitated accurate compliance monitoring throughout the study. The training volumes were derived and/or adapted from previous NHE literature.[4,9]

Eccentric knee flexor strength testing

Eccentric knee flexor strength was assessed prior to each participant's first training session, post intervention, and after 2 and 4 weeks of detraining. Prior to testing, participants completed a warm-up of one repetition at 50%, 75%, and 90% of perceived maximum effort. Following two minutes of rest, participants were instructed to complete one set of three repetitions of maximal NHE repetitions. The largest strength value from each limb was determined, and the two-limb average was calculated.

Ultrasound assessment

Muscle thickness, pennation angle, and fascicle length of the BFlh were determined from images taken along the longitudinal axis of the muscle belly utilizing a two-dimensional, Bmode ultrasound (frequency 12 MHz; depth 8 cm; field of view (FOV) 14×47 mm) (Logiq E, GE Healthcare, IL, USA) similar to previous methods.[15-17] The scanning site was determined as the halfway point between the ischial tuberosity and the knee joint fold, along the line of the BFlh. To gather the ultrasound images, a linear array probe with a layer of conductive gel was placed on the skin over the scanning site, aligned longitudinally and perpendicular to the posterior thigh with the participant prone and the knee fully extended. The probe was then manipulated until the superficial and intermediate aponeuroses were parallel.[17]Analysis was undertaken offline (MicroDicom, Version 0.7.8, Bulgaria). Muscle thickness was determined as the distance between the superficial and intermediate aponeuroses of the BFlh. A fascicle of interest was outlined and marked on the image. The angle between this fascicle and the intermediate aponeurosis was measured as the pennation angle, this angle was then confirmed with at least two parallel fascicles. The aponeurosis angle for both aponeuroses was determined as the angle between the line marked as the aponeurosis and an intersecting horizontal line across the captured image. Fascicle length was determined as the length (in cm) of the average of three outlined fascicles between the aponeuroses. Because the entire fascicles were not visible in the field of view, they were estimated using an equation which was previously validated against cadaveric hamstring tissue.[18]

$$FL = \sin(AA + 90°) \times MT/\sin(180° - (AA + 180° - PA))$$

where FL = fascicle length, AA = aponeurosis angle, MT = muscle thickness and PA = pennation angle.

The same assessor (FPB) collected and analyzed all scans and was blinded to participant identifiers during the analysis. Reliability of the assessor (FPB) and processes used for BFlh architectural determination was determined in a prior pilot study of 14 repeated samples (fascicle length: Intraclass correlation coefficient (ICC) 0.924, standard error of measure

(SEM) 0.34 cm, minimal detectable change (MDC) 0.94 cm; pennation angle: ICC .953, SEM 0.37°, MDC 1.03°; muscle thickness: ICC 0.905, SEM 0.05 cm, MDC 0.14 cm).

Statistical analysis

All statistical analyses were performed using the R statistical programming language[19] and the following packages: dplyr, lme4 and car. Where appropriate, data were screened for normality using the Shapiro-Wilk test and homoscedasticity using Levene's test. The training data analyses consisted of a set of linear mixed models fitted to assess changes in the outcome variables (BFlh FL, pennation angle, muscle thickness, and NHE strength) from baseline (week 1) to post-test. The de-training data analyses consisted of a set of linear mixed models fitted to assess changes in each of the outcome variables across the de-training period (post-test, de-training week 2 and de-training week 4). For each outcome variable, covariates were group (1, 2, 3, or 4) and time, with participant ID included as a random effect to account for repeated measures. Where significant main or interaction effects were detected, post-hoc t-tests (paired for within-group comparisons, unpaired for between-group comparisons) were used to determine where any differences occurred. Significance was set at $p < 0.05$ and where possible Cohen's d was reported for the effect size of the comparisons, with the levels of effect being deemed small ($d = 0.20$ to 0.49), medium ($d = 0.50$ to 0.79) or large ($d \geq 0.80$).[20] All data were expressed as mean ± SD, unless otherwise stated. Missing data were identified and handled using pairwise deletion (i.e. specific to the variable being analysed). Only complete observations were included when conducting the paired t-tests. A sample size of 40 participants was deemed sufficient using G*Power. These calculations were based on estimated differences in fascicle length following the intervention with an effect size of 1.25, power set at 80%, an alpha level of <0.05, and accounting for a 10% drop out rate.[2,9]

RESULTS

The demographic data for each group as can be found in Supplementary Material 1. There were no differences in participant age, height, or body mass between the groups ($p > 0.05$). Compliance to the interventions was 97% or above in all groups. 10 participants required added weight plates to continue to achieve overload after 3-4 weeks of training, 80% of these were in the higher volume training groups (Groups 3 and 4). All FL data for each group can be found in Figure 2 (A-D). Mean FL in each group can be observed in Supplementary Material 2. All NHE strength data for each group can be found in Figure 3 (A-D). Mean NHE strength in each group can be observed in Supplementary Material 3. FL and strength for each group from baseline to post-test and post-test to de-training week 4 have been illustrated in Figure 4A and Figure 4B respectively. Additionally, weekly NHE strength values throughout the intervention can be observed in Supplementary Material 4.

Biceps femoris long head architecture

Fascicle length

A significant main effect for time was observed for BFlh FL ($p < 0.001$). There was no effect for group ($p = 0.529$) or the interaction between group and time ($p = 0.147$). Post-hoc analyses of within-group changes over time showed that following six weeks of training, BFlh FL increased in Group 3 (mean difference = 0.83 cm, $d = 0.45$, $p = 0.027$, +7%) and Group 4 (mean difference = 1.48 cm, $d = 0.94$, $p = 0.004$, +14%). Following four weeks of de-training (post-test to de-training week 4) BFlh FL in Group 3 and Group 4 significantly decreased (Group 3: mean difference = -1.26 cm, $d = -0.84$, $p = 0.006$, -10%; Group 4: mean difference = -1.22 cm, $d = -0.61$, $p = 0.009$, -10%).

Pennation angle

A significant main effect for time was observed for pennation angle (p = 0.022). There was no effect for group (p = 0.975) or the interaction between group and time (p = 0.052). Post-hoc analyses of within-group changes over time showed that following six weeks of training (baseline to post-test), pennation angle decreased in Group 3 (mean difference = -0.87 degrees, d = -0.45, p = 0.034, -6%) and Group 4 (mean difference = -1.04 degrees, d = -0.80, p = 0.019, -8%). Following four weeks of de-training (post-test to de-training week 4), pennation angles in Group 3 and Group 4 significantly increased (Group 3: mean difference = 0.98 degrees, d = 0.58, p = 0.030, +8%; Group 4: mean difference = 1.24 degrees, d = 0.67, p = 0.034, +10%).

Muscle thickness

A significant main effect for time was observed for muscle thickness (p < 0.001). There was no effect for group (p = 0.263) or the interaction between group and time (p = 0.094). Post-hoc analyses of within-group changes over time showed that following six weeks of training, muscle thickness increased in Group 1 (Group 1: mean difference = 0.17 cm, d = 0.52, p = 0.045) and Group 4 (mean difference = 0.10 cm, d = 0.42, p = 0.015). Following two weeks of de-training (post-test to de-training week 2), muscle thickness decreased in Group 4 (mean difference = -0.16 cm, d = -0.86, p = 0.019).

Eccentric knee flexor strength

A significant main effect for time was observed for NHE strength (p < 0.001). There was no effect for group (p = 0.474). However, there was a significant interaction between group and time (p = 0.003). Post-hoc analyses of within-group differences over time showed that following six weeks of training, NHE strength increased in Group 2 (mean difference 53.6 N, d = 0.55, p = 0.002, +14%), Group 3 (mean difference = 63.4 N, d = 0.72, p = 0.027, +17%), and Group 4 (mean difference = 74.7, d = 0.83, p = 0.006, +19%). Additionally, post-hoc analyses of between-group differences showed that Group 4 was significantly stronger than Group 1 at post-test (mean difference = 94.2 N, d = 1.09, p = 0.028, +25%). Following four weeks of de-training (post-test to de-training week 4), strength in Group 3 significantly decreased (mean difference = -33.9 N, d = -0.45, p = 0.003, -8%).

DISCUSSION

Low volume NHE exposures (24 or 48 total repetitions across six weeks) was insufficient to increase BFlh fascicle length, although, as few as 48 repetitions in six weeks increased eccentric knee flexor strength. Six weeks of an NHE training program, consisting of either an a) initial high volume followed by low volume (Group 3, 176 total repetitions) or b) progressively increasing volume (Group 4, 358 total repetitions) resulted in significant increases in BFlh FL and a commensurate decrease in PA, whereas exposure to lower volumes (Group 1, 24 total repetitions; Group 2, 48 total repetitions) did not. Furthermore, within-group increases in strength were observed in all NHE training groups, except for the lowest volume training group (24 total repetitions). All increases in BFlh FL and strength returned to baseline following four weeks of de-training, except for the highest volume training group (358 total repetitions), which maintained increased strength following de-training.

Research examining the relationship between NHE volume and adaptations of BFlh FL and strength have been restricted to comparisons between a "high" and "low" volume prescription.[9, 13] Presland et al.[9] compared two different six-week NHE training protocols, an initial high volume followed by low volume (128 total repetitions) or a progressively increasing volume protocol (440 total repetitions). Both groups similarly increased BFlh FL (24% and 23%, respectively) and strength (33% and 28%, respectively). Whilst the current study did not incorporate identical NHE prescriptions,[9] Groups 3 and 4, which represent the most analogous groups, also reported no between groups differences in either BFlh FL (8% and 14%, respectively) or strength (21% and 19%, respectively) following the intervention.

Other work comparing NHE protocols of different volumes, also included a bilateral stiff-legged deadlift,[13] so attributing variations between groups solely to the NHE is impossible. The work by Lacome et al.[13] compared two different protocols, consisting of a single weekly exposure of either 4 repetitions (in conjunctions with 6 deadlift repetitions) or 16 repetitions (in conjunction with 24 deadlift repetitions) of the NHE across a six-week period in a cross-over study design. They found no difference between the "high" and "low" volume groups for BFlh FL (both groups increased ~5% compared to baseline),[13] in alignment with the current work which found a 3-6% increase across Groups 1 and 2, with no statistical difference between groups. Whilst the findings from Group 2 in the current study showed a similar increase in strength (15%) compared to the two groups from Lacome et al. (11%),[13] Group 1 showed no change (-1%) in strength. Of the NHE volume literature, Group 1 from the current study is the only protocol with a training frequency of less than one per week and this may account for the discrepancy. This suggests that whilst training volume (total number of NHE repetitions) has been a primary focus of recent literature,[9,13] training frequency may deserve further attention, particularly as BFlh architecture is known to change as quickly as two weeks following the introduction or removal of a training stimulus[8, 9, 21] and tends to decay across a season.[15]

The current work, in conjunction with prior work examining hamstring strength adaptations,[7-9, 13, 21, 22] should provide guidance to practitioners around how best to program the NHE to elicit favourable changes in BFlh architecture. Low volume exposures to the NHE without an initial period of higher volumes (i.e. Group 1 and 2 from the present study and the "low" volume group from Lacome et al.),[13] appears to not provide a sufficient stimulus to increase BFlh FL. Such protocols, ranging between 24 to 48 repetitions across a six-week intervention period resulted in BFlh FL increases of 2 to 5%. It is noteworthy that the "low" volume protocol in Presland et al. incorporated an initial two-week period of higher volume exposures (48 weekly repetitions) which then transitioned into a four-week block of 8 weekly repetitions.[9] During this four-week low volume period there was a 5% increase in BFlh FL, whilst the initial higher volume two-week period resulted in a ~20% increase. Consequently, it might be tempting to suggest that higher volume NHE exposure, perhaps during an early pre-season training block, before shifting into a low volume maintenance phase, might be beneficial for more substantial alterations in BFlh architecture. It would appear prudent to provide an eccentric strength training stimulus at a minimum once weekly to maintain BFlh FL. Furthermore, a period of high-volume exposures (~48 weekly repetitions), is more likely to lead to larger increases in BFlh FL.

Regarding eccentric knee flexor strength, the current findings suggest that the required prescription of the NHE to increase strength may be different to what is necessary to drive adaptation in BFlh FL. All protocols which included weekly exposure to the NHE across the six-week period resulted in improvements in strength, despite variations in total repetitions (48 vs 176 vs 358 repetitions). The only protocol that did not induce increases in strength involved exposures to the NHE in low volumes (8 repetitions) once per fortnight. Thus, a minimum frequency of NHE exposures may be more important than a minimum volume for strength adaptations. The literature regarding increasing maximal strength more broadly, indicate that low volume, high intensity exposures to resistance exercise is a potent stimulus to increase strength.[23] Hence, it is not surprising that a low volume prescription in the current paper (Group 2) had significant improvements in strength, given the high intensity of the NHE.

This study has limitations that may have impacted the findings. The measure of BFlh FL is an estimation made from a validated equation.[17, 24] This estimation is required due to the small transducer field of view utilized that is unable to capture an entire BFlh fascicle. The methodology and equation employed for this estimation was chosen as this was the technique used when BFlh FL was found to be associated with injury prospectively,[2] as this technique has been found to be reliable,[17] and this method has been compared against cadaveric hamstring samples and has shown acceptable agreement[18]. However, other methods such as extended field of view ultrasound,[25] three-dimensional ultrasound,[26] or enhanced clinically feasible diffusion tensor imaging[27] may provide different insights in to training-induced changes of BFlh architecture. Minimal clinically important difference values have not been established for architectural or strength measures as no intervention has directly investigated whether changes in both BFlh FL and eccentric knee flexor strength values are required for the preventative effect of the NHE to be realised. Group 1 completed a very low volume of exercise (2 sets of 4 repetitions every second week) to allow monitoring of strength throughout the trial and to act as a pseudo-control group while still facilitating strength assessment. It has previously been demonstrated that BFlh FL does not change during a non-exercising control period.[21] Finally, the participants of this study were recreationally active males, and it is unknown how these findings may translate to more highly trained cohorts.

Practical Applications

Initial high volumes of the Nordic hamstring exercise followed by lower volumes, as well as progressively increasing volumes, can elicit significant increases in BFlh fascicle length and eccentric knee flexor strength. Lower volumes protocols, completed at least once a week, can increase eccentric knee flexor strength but may not be sufficient to increase BFlh fascicle length without a period of initial higher volumes. These findings may help guide practitioners in programming the Nordic hamstring exercise to strike the most appropriate balance between driving adaptation in hamstring injury risk factors whilst achieving appropriate levels of compliance.

Conclusion

Initial high volumes of the NHE followed by low volume maintenance exposure as well as progressively increasing volume protocols elicit significant increases in BFlh FL and eccentric knee flexor strength. Lower volumes protocols, completed at least once per week, can increase strength, but may not be sufficient to increase BFlh FL.

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Figure captions:

Figure 1. CONSORT flow diagram.

Figure 2. Absolute biceps femoris long head (BFlh) fascicle length at each timepoint for A) Group 1, B) Group 2, C) Group 3 and D) Group 4. The black squares indicate the mean, and the grey circles illustrate participants' individual data. The dashed horizontal line indicates the group mean at baseline. Asterisks (*) indicate a significant difference (p = < 0.05) between absolute values at the corresponding timepoint and absolute values at week 1 (baseline). Hashes (#) indicate a significant difference (p = < 0.05) between absolute values at the corresponding timepoint and absolute values at post-test. Group 1 = intermittent low volumes, Group 2 = low volumes, Group 3 = initial high volumes followed by low volumes, Group 4 = progressively increasing volumes.

Figure 3. Absolute eccentric knee flexor strength at each timepoint for A) Group 1, B) Group 2, C) Group 3 and D) Group 4. The black squares indicate the mean, and the grey circles illustrate participants' individual data. The dashed horizontal line indicates the group mean at baseline. Asterisks (*) indicate a significant difference (p = < 0.05) between absolute values at the corresponding timepoint and absolute values at week 1 (baseline). Hashes (#) indicate a significant difference (p = < 0.05) between absolute values at the corresponding timepoint and absolute values at post-test. Group 1 = intermittent low volumes, Group 2 = low volumes, Group 3 = initial high volumes followed by low volumes, Group 4 = progressively increasing volumes.

Figure 4. Changes in biceps femoris long head (BFlh) fascicle length and eccentric knee flexor strength from A) baseline to post-test and B) post-test to end of de-training (de-training week 4). The transparent points/lines display individual participants' data, whereas the solid points/lines display the means for each group. In Figure 4A, the open points indicate baseline and the closed points indicate post-test. In Figure 4B the open points indicate post-test and the closed points indicate end of de-training. Group 1 = intermittent low volumes, Group 2 = low

volumes, Group 3 = initial high volumes followed by low volumes, Group 4 = progressively increasing volumes.

Table 1. Nordic hamstring exercise training prescription for all four groups.

Supplementary Materials:

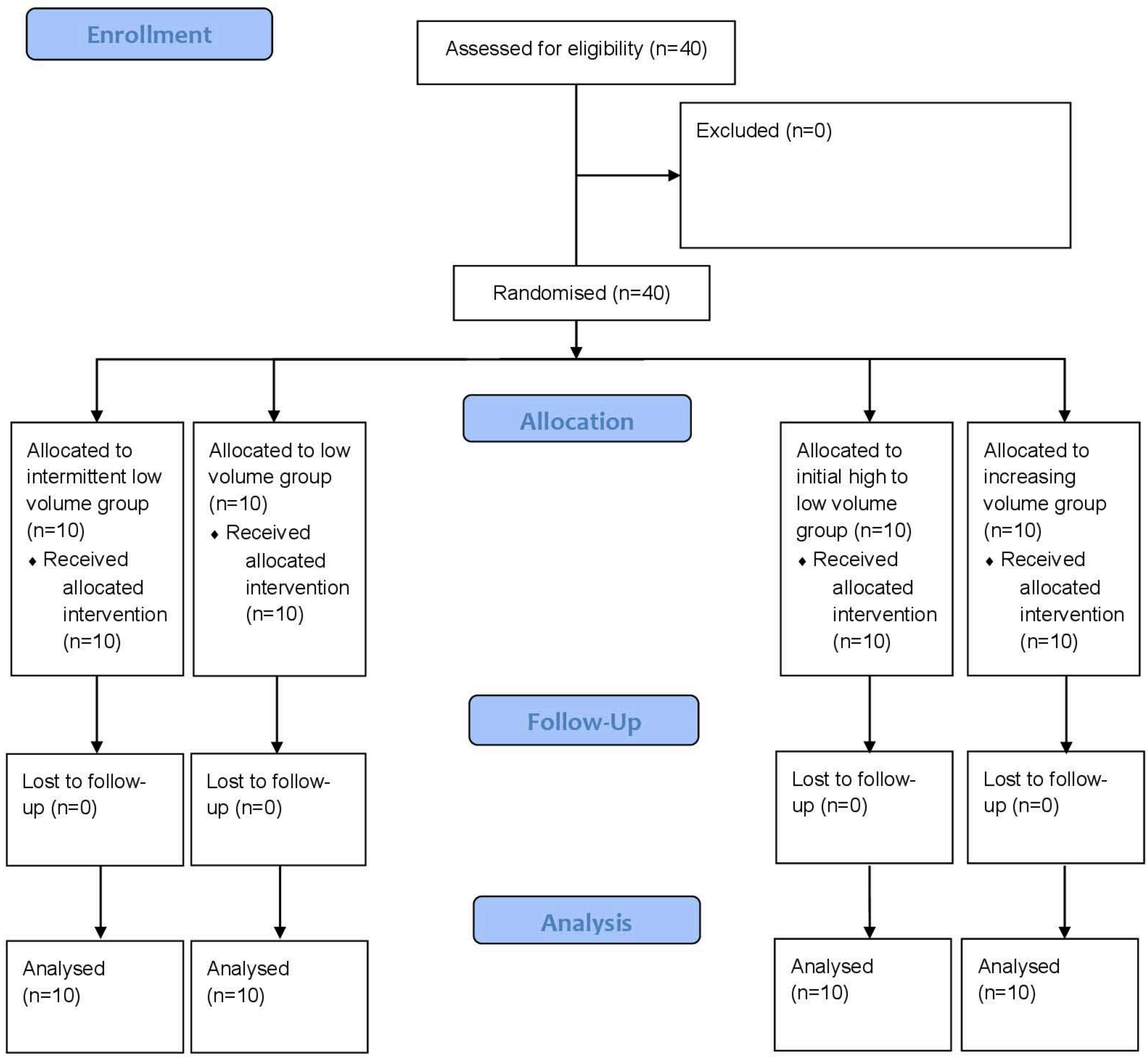
Supplementary Material 1. Demographic data for each group. These data are presented in mean values (± standard deviation). N = 10 per each group.

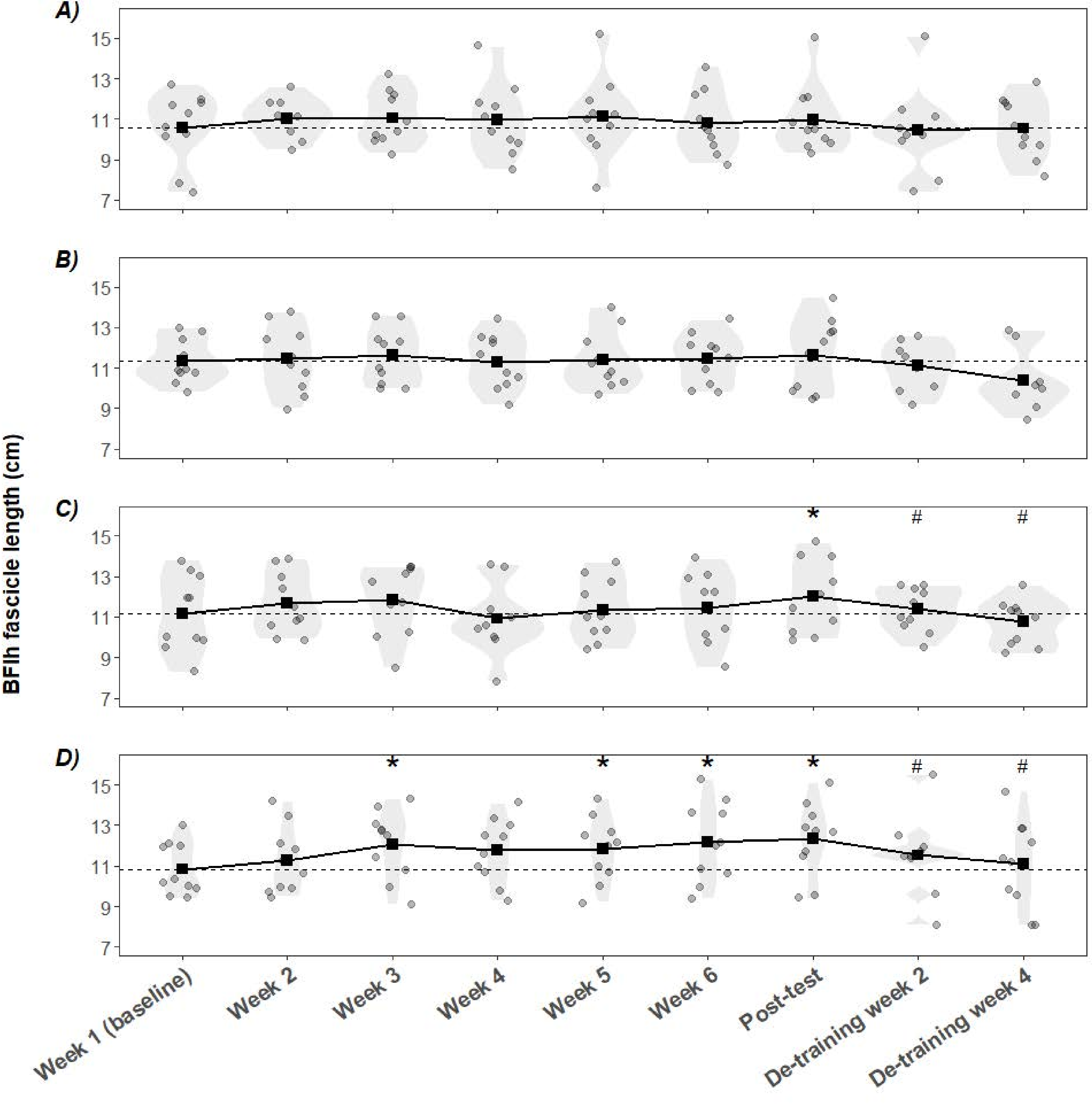
Supplementary Material 2. Biceps femoris long head fascicle length (cm) for all groups at all testing time points. These data are presented in mean values (± standard deviation). N = 10 per group.

Supplementary Material 3. Eccentric knee flexor strength (N) for all groups at all testing time points. These data are presented in mean values (± standard deviation). N = 10 per each group.

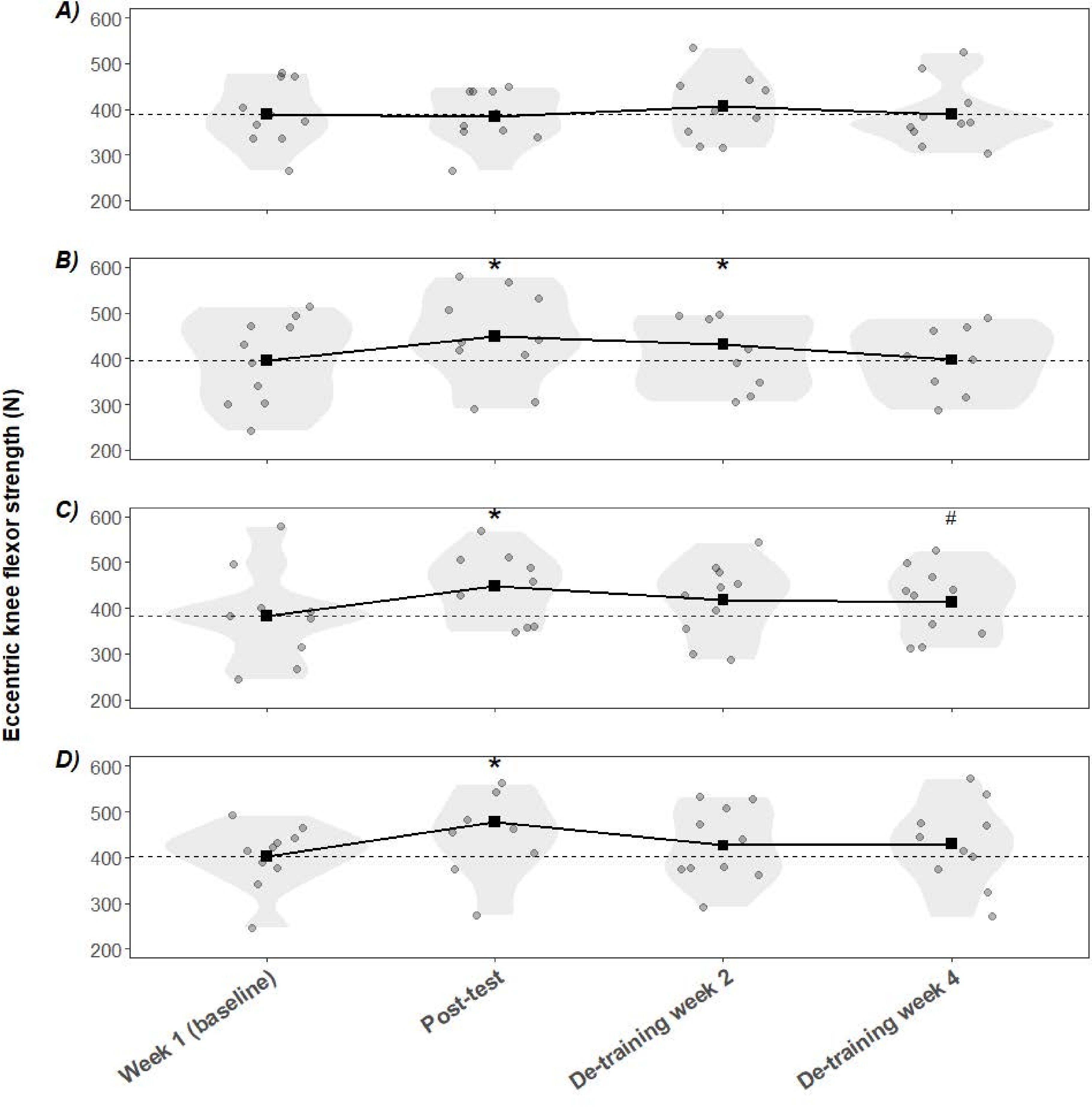
Supplementary Material 4. Weekly maximal eccentric knee flexor strength values (N) for all groups throughout the intervention and de-training period. These data are presented in mean values (± standard deviation). N = 10 per each group.

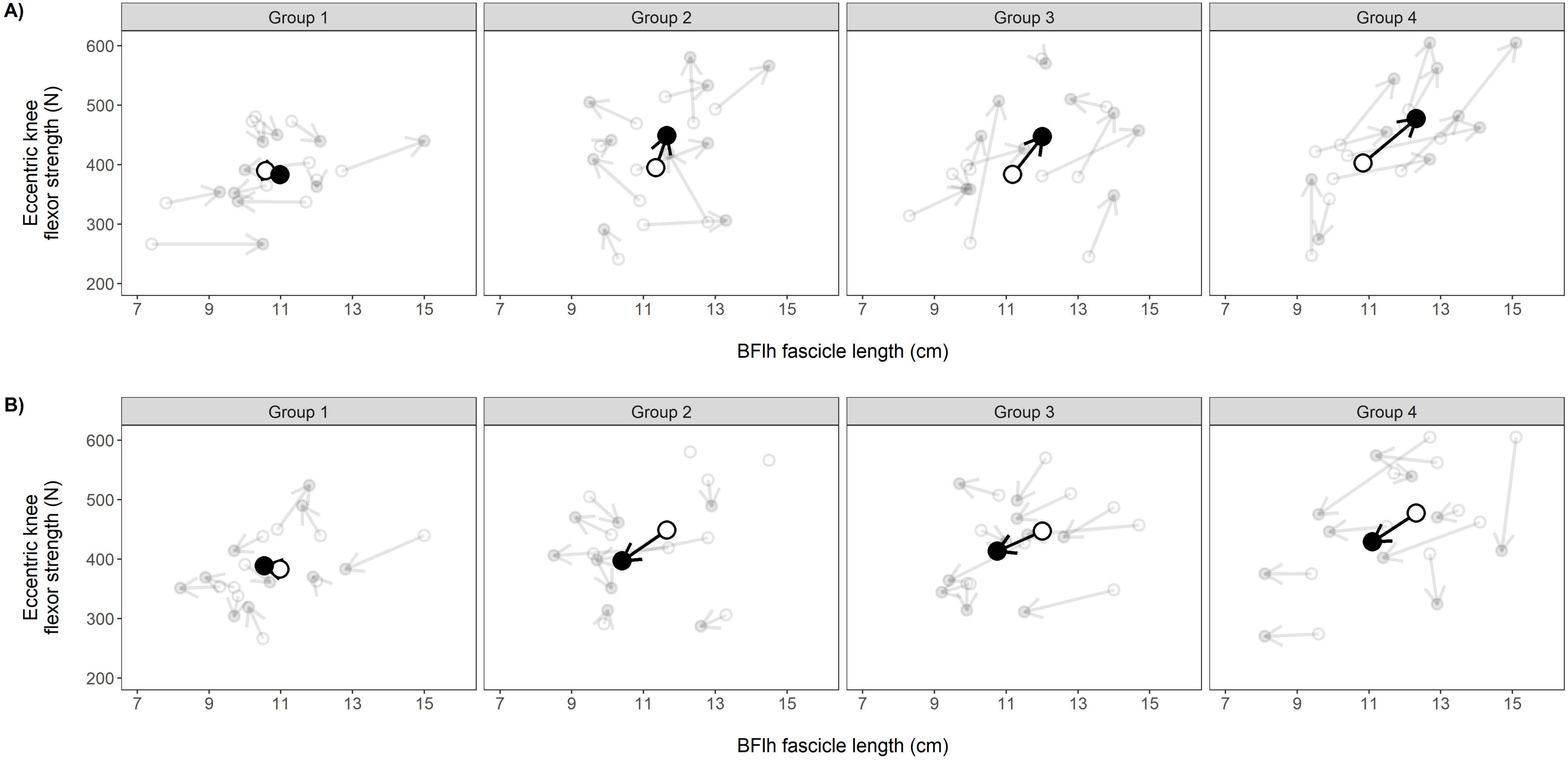
CONSORT Flow Diagram





A)
B)
C)
D)
BFlh fascicle length (cm)
15
13
11
9
7
*
#
Week 1 (baseline)
Week 2
Week 3
Week 4
Week 5
Week 6
Post-test
De-training week 2
De-training week 4


A)
B)
C)
D)
600
500
400
300
200
*
#
Eccentric knee flexor strength (N)
Week 1 (baseline)
Post-test
De-training week 2
De-training week 4



A)
Group 1
Group 2
Group 3
Group 4
Eccentric knee flexor strength (N)
BFlh fascicle length (cm)
B)
Group 1
Group 2
Group 3
Group 4
Eccentric knee flexor strength (N)
BFlh fascicle length (cm)

TABLE 1. Nordic hamstring exercise training prescription for all four groups.

Group	Week	Frequency	Sets	Reps	Total Reps
Group 1: Minimal volume/ quasi-control	1	1	2	4	8
	2	0	0	0	0
	3	1	2	4	8
	4	0	0	0	0
	5	1	2	4	8
	6	0	0	0	0
Group 2: Low volume	1	1	2	4	8
	2	1	2	4	8
	3	1	2	4	8
	4	1	2	4	8
	5	1	2	4	8
	6	1	2	4	8
Group 3: Initial high volume followed by low volume	1	3	4	6	72
	2	3	4	6	72
	3	1	2	4	8
	4	1	2	4	8
	5	1	2	4	8
	6	1	2	4	8
Group 4: Progressively increasing volume	1	1	2	5	10
	2	2	2	6	24
	3	3	3	7	63
	4	3	3	9	81
	5	3	3	12, 10, 8	90
	6	3	3	12, 10, 8	90

Supplementary Material 1. Demographic data for each group. These data are presented in mean values (± standard deviation). N = 10 per each group.

Group	Age (years)	Height (cm)	Mass (kg)
Group 1: minimal volume	32 ± 4	181 ± 5	79 ± 8
Group 2: low volume	32 ± 4	180 ± 5	79 ± 8
Group 3: initial high volume followed by low volume	33 ± 4	181 ± 8	86 ± 9
Group 4: progressively increasing volume	31 ± 5	182 ± 9	86 ± 11

Supplementary Material 2. Biceps femoris long head fascicle length (cm) for all groups at all testing time points. These data are presented in mean values (± standard deviation). N = 10 per group.

Group	Week 1 (baseline)	Week 2	Week 3	Week 4	Week 5	Week 6	Post-test	De-training week 2	De-training week 4
Group 1: minimal volume	10.6 ± 1.7	11.0 ± 1.0	11.0 ± 1.3	11.0 ± 1.8	11.1 ± 2.0	10.8 ± 1.5	11.0 ± 1.7	10.5 ± 2.2	10.5 ± 1.5
Group 2: low volume	11.3 ± 1.1	11.5 ± 1.7	11.6 ± 1.4	11.3 ± 1.3	11.4 ± 1.4	11.5 ± 1.2	11.7 ± 1.8	11.1 ± 1.2	10.4 ± 1.6
Group 3: initial high volume followed by low volume	11.2 ± 1.9	11.7 ± 1.5	11.8 ± 1.8	10.9 ± 1.8	11.4 ± 1.5	11.4 ± 1.5	12.0 ± 1.8*	11.4 ± 1.1#	10.7 ± 1.1#
Group 4: progressively increasing volume	10.8 ± 1.3	11.3 ± 1.6	12.1 ± 1.7*	11.8 ± 1.6	11.8 ± 1.6*	12.2 ± 2.0*	12.3 ± 1.8*	11.5 ± 2.0#	11.1 ± 2.2#

* indicates a significant difference (P = < 0.05) compared to week 1 (baseline)

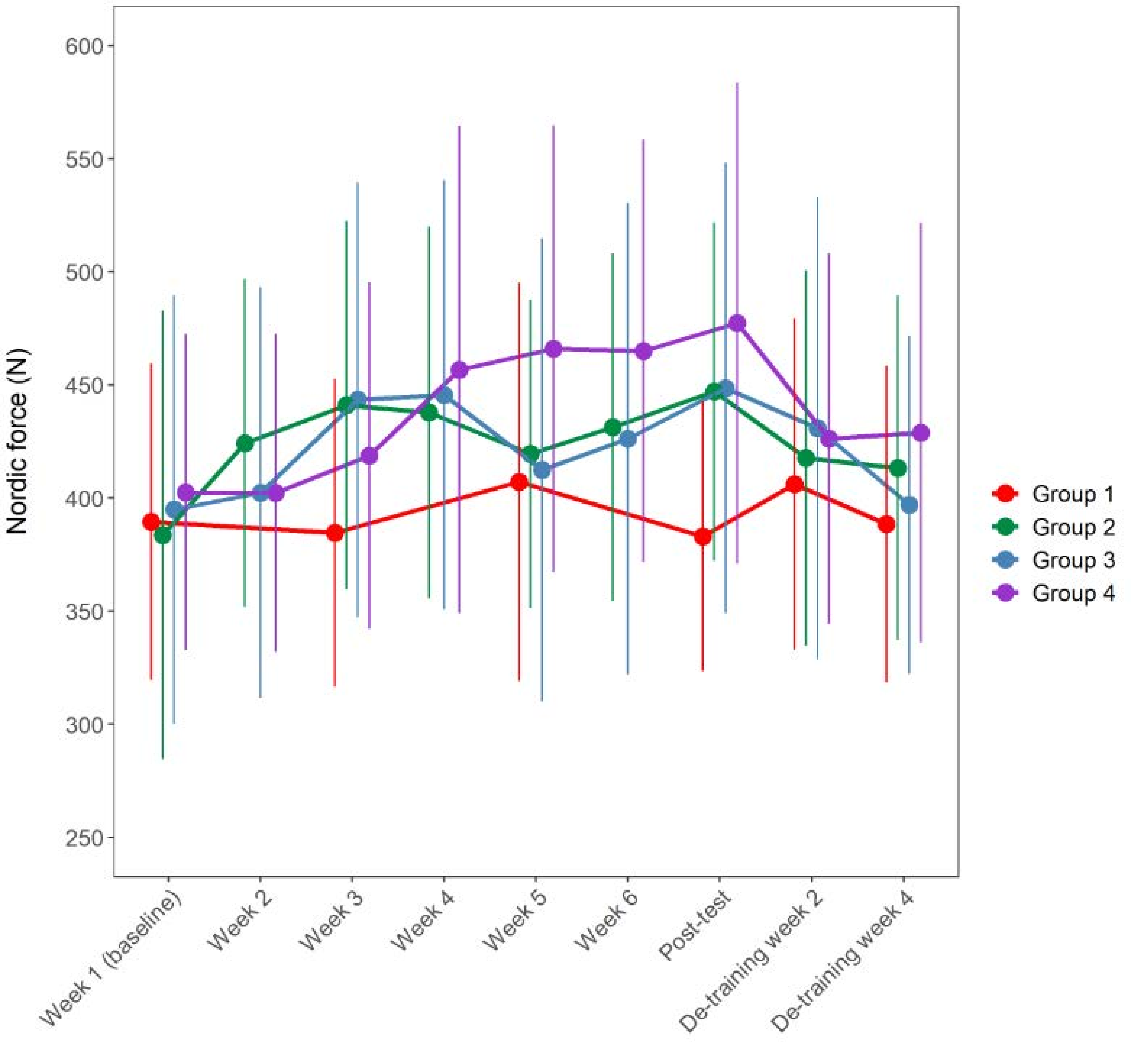
# indicates a significant difference (P = < 0.05) compared to post-test

Supplementary Material 3. Eccentric knee flexor strength (N) for all groups at all testing time points. These data are presented in mean values (± standard deviation). N = 10 per each group.

Group	Week 1 (baseline)	Post-test	De-training week 2	De-training week 4
Group 1: minimal volume	389 ± 70	383 ± 60	406 ± 73	388 ± 70
Group 2: low volume	395 ± 95	448 ± 99*	431 ± 102*	397 ± 75
Group 3: initial high volume followed by low volume	384 ± 99	447 ± 75*	417 ± 83	413 ± 76#
Group 4: progressively increasing volume	402 ± 70	477 ± 107*	426 ± 82	429 ± 93

* indicates a significant difference (P = < 0.05) compared to week 1 (baseline)

# indicates a significant difference (p = < 0.05) compared to post-test



Nordic force (N)
600
550
500
450
400
350
300
250
Week 1 (baseline)
Week 2
Week 3
Week 4
Week 5
Week 6
Post-test
De-training week 2
De-training week 4
Group 1
Group 2
Group 3
Group 4