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Individual distribution of muscle hypertrophy among hamstring muscle heads: Adding muscle volume where you need is not so simple

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Abstract

Purpose: The aim of this study was to determine whether a 9-week resistance training program based on high load (HL) versus low load combined with blood flow restriction (LL-BFR) induced a similar (i) distribution of muscle hypertrophy among hamstring heads (*semimembranosus*, SM; *semitendinosus*, ST; and *biceps femoris* long head, BF) and (ii) magnitude of tendon hypertrophy of ST, using a parallel randomized controlled trial.

Methods: A total of 45 participants were randomly allocated to one of three groups: HL, LL-BFR, and control (CON). Both HL and LL-BFR performed a 9-week resistance training program composed of seated leg curl and stiff-leg deadlift exercises. Freehand 3D ultrasound was used to assess the changes in muscle and tendon volume.

Results: The increase in ST volume was greater in HL (26.5 ± 25.5%) compared to CON ($p = 0.004$). No difference was found between CON and LL-BFR for the ST muscle volume ($p = 0.627$). The change in SM muscle volume was greater for LL-BFR (21.6 ± 27.8%) compared to CON ($p = 0.025$). No difference was found between HL and CON for the SM muscle volume ($p = 0.178$).There was no change in BF muscle volume in LL-BFR (14.0 ± 16.5%; $p = 0.436$) compared to CON group. No difference was found between HL and CON for the BF muscle volume ($p = 1.0$). Regarding ST tendon volume, we did not report an effect of training regimens ($p = 0.411$).

Conclusion: These results provide evidence that the HL program induced a selective hypertrophy of the ST while LL-BFR induced hypertrophy of SM. The magnitude of the selective hypertrophy observed within each group varied greatly between individuals. This finding suggests that it is very difficult to early determine the location of the hypertrophy among a muscle group.

KEYWORDS

hamstring, individual hypertrophy, muscle volume, resistance training

1 | INTRODUCTION

The hamstring muscles play an important role in many sports. It is thought that hamstring muscle strengthening is necessary to improve sports performance[1] and reduce the risk of muscle and anterior cruciate ligament (ACL) injuries,[2] among other benefits. Therefore, it is important to optimize strengthening programs that aims to induce hypertrophy, and blood flow restriction (BFR) has been suggested as a relevant method for achieving this aim.[3] This method allows individuals to reach, at low load, muscle failure approximately 30% faster.[3] Muscle failure is crucial to maximize muscle hypertrophy at low load (for review, see Grgic et al.[4]). Thus, low load with BFR is effective at inducing hypertrophy which is particularly useful in clinical settings, where the ability of an individual to lift high load is reduced (e.g., rehabilitation after an ACL reconstruction).[5] Thus, a better understanding of BFR training effects is currently a topic of high interest.

Following 10 weeks of training, Bourne et al.[6] found that Nordic hamstring exercise favored the hypertrophy of *semitendinosus* [ST (21%)] compared to *semimembranosus* [SM (5%)] and *biceps femoris* long head [BFlh (6%)], while the 45° hip extension exercise induced a more balanced hypertrophy between muscles. In this study, participants from the Nordic hamstring group performed eccentric contractions at a supramaximal resistance exclusively (i.e., the participants were not able to resist until the full range of motion) while participants from the 45° hip extension group performed the exercise at 60%–80% of the maximal repetition (1-RM). It is currently unknown whether the differences in hamstring hypertrophy distribution originates from either the movement orientations (knee vs. hip) or relative loads (supramaximal vs. submaximal). If the magnitude of the load is involved, can training at high load versus low load BFR also induce selective hypertrophies among hamstring muscles? This question is crucial to better understand the effects of strengthening programs using BFR.

In an orthopedic surgery context, the patella tendon and the semitendinosus tendon are the most utilized grafts after ACL rupture. Studies involving uninjured participants have demonstrated that resistance training is effective in increasing cross-sectional area in the patellar tendon.[7,8] For instance, Malliaras et al.[8] reported an increase of 5 ± 7% in cross-sectional area of the patellar tendon after 9 weeks of concentric resistance training performed at 80% of the 1-RM. More recently, Centner et al.[9] reported that tendon hypertrophy (approximately10% in patellar tendon) was observed at low load (20%–35% of the 1-RM) combined with BFR. Concerning ST tendons, if the cross-section of these grafts is smaller than 8 mm, the relative risk for graft failure is nearly seven times greater.[10] Hence, it could be beneficial to perform resistance training before surgery in order to induce tendon hypertrophy. It has been shown that ST exhibited the largest hypertrophic response among hamstring muscles in elite sprinters[11] and after strength training programs.[6,12] Thus, ST represents a good candidate to study tendon hypertrophy in the perspective of preoperative resistance training for ACL graft.[10] To the best of our knowledge, no studies have investigated ST tendon hypertrophy, regardless of the load applied during training.

Using a randomized controlled trial design, the current study aims were to determine whether a 9-week resistance training program based on high load (12-RM) versus low load (30-RM) combined with BFR induced a similar (i) distribution of muscle hypertrophy among hamstring heads and (ii) magnitude of tendon hypertrophy of ST. Due to differences in the magnitude of load,[6] we hypothesized that the high load (HL), and low load with BFR (LL-BFR) programs would lead to a different distribution of muscle hypertrophy among hamstring heads. In accordance with a recent study conducted in the Achilles tendon using BFR,[13] we also hypothesized a significant tendon hypertrophy of ST, regardless of the load.[9]

2 | METHODS

2.1 | Participants

Forty-five recreationally active participants, that is, performing physical activity (team sports, running, etc.), of which 14 were women, volunteered to participate (age = 22.0 ± 3.3 years; height = 175 ± 8.7 cm; mass = 69.2 ± 8.6 kg). Note that the participants were accustomed to strengthening practice but were not currently engaged in hamstring strengthening exercises. All participants were recruited at the Faculty of Sports Sciences that require at least 8 h of sport activities weekly. Potential participants that undergo any form of resistance training (e.g., gym, Crossfit, and strength training) at the moment of inclusion were deemed not eligible for the trial. Participants had no recent lower limb injury within last 6 months, no limitation of the function of their knee, and did not require any intervention from a health care professional. Participants with a contraindication to having BFR training were also excluded.[14] Before inclusion, participants were informed about the study risks and hypothetic advantages and then gave their written consent. The study was approved by the ethics committee (n°2021-A02993-38), and all the experiments were conducted in accordance with the latest version of the Declaration of Helsinki.

2.2 | Experimental design

A parallel randomized controlled trial design was implemented to compare the effect of 9 weeks of HL or LL-BFR resistance training on the distribution of hamstring muscle hypertrophy and the magnitude of ST tendon hypertrophy. Participants were randomly allocated to one of three groups: HL, LL-BFR, and control (CON) using Research Randomizer (Urbaniak and Plous, 2007). All participants underwent two identical assessment sessions the week before and after the training program (pre- and post-, respectively). Assessments were composed of (i) freehand 3D ultrasound (3DUS) measurements of hamstring muscle volume and ST tendon volume and (ii) maximal isometric voluntary contractions of knee flexors (e.g., maximal force). Assessors were blinded to group allocation during the testing sessions. All measurements and training sessions were supervised and completed at the Faculty of Sports Sciences at Nantes University (France).

2.3 | Resistance training program procedures

The protocol consisted of a total of 27 training sessions performed over 9 weeks. For the experimental groups (HL and LL-BFR), training consisted of three sessions weekly, while the CON group continued their regular sport activities, and were asked not to start any new activities.

Two training sessions (a & b) that used different exercises were alternated over the duration of the training program: the session (a) was composed of stiff-leg deadlift and front squat, and the session (b) was composed of a bi-set of bilateral seated leg curl and seated leg extension. Each session was started by a 10-min standardized warm up.

2.3.1 | High-load training program (HL)

In Weeks 1–3, each HL training session consisted of three sets of each exercise and thereafter this was increased up to five sets over the remaining weeks. The number of sets were adjusted every 3 weeks to match the training load between groups (see details in section: "Quantification of training load"). During the first training session and every 3 weeks, the maximal load that enabled the participants to perform 12 repetitions (i.e., 12-RM) was determined for each exercise.[15] For a progressive increase in training load over the 9 weeks, participants performed a maximum of repetitions with two to three repetitions in reserve (i.e., rating of perceived exertion 8 (RPE)), during the first 3 weeks, and performed maximum of repetitions to failure each set from Weeks 4–9. A resting period of 1.5 min was used between the sets.

2.3.2 | Low load combined with blood flow restriction (LL-BFR)

Each LL-BFR training session consisted three sets of each exercise (stiff-leg deadlift and front squat (session a) or seated leg curl and seated leg extension (session b)). During the first training session and every 3 weeks thereafter, the maximal load for performing 30 repetitions was determined for each exercise involving BFR (i.e., 30-RM[15]). Each set of LL-BFR training session was performed utilizing the MAD-UP Pro BFR device (Angers, France, 2020). Two 10.5 cm cuffs were positioned on each leg at the most proximal aspect of the thigh. Then, 80% of arterial occlusion pressure was applied in a supine lying position at the beginning of each set.[16] A resting period of 1.5 min was used between sets. During rest, the occlusion was set at 30% arterial occlusion. For a progressive increase in training load over the 9 weeks, participants performed a maximum of repetitions with two to three repetitions in reserve (i.e., RPE 8) during the first 3 weeks, and thereafter from Weeks 4–9 performed a maximum of repetitions to failure for each set.

2.4 | Muscle and tendon volume

Briefly, ultrasound imaging was used to obtain two-dimensional B-mode images (Aixplorer version 12.3 scanner, SuperSonic Imagine, Aix-en-Provence, France), using a 10–2 linear transducer (40 mm field of view; Vermon, Tours, France) and a 20–6 linear transducer (32 mm field of view; SuperLinearTM SLH20-6; SuperSonic Imagine; Aix-en-Provence, France) for muscle and for tendon acquisitions, respectively. Image depth was set at 8.5 cm for muscle and 3.5 cm for tendons acquisitions. B-mode images were recorded using a video grabber (ElGato Cam Link; Corsair Components; Fremont, CA). An optoelectronic motion capture system collecting at 120 Hz (six cameras Optitrack Flex 13, NaturalPoint, USA) recorded 3D positions of the transducers by tracking a 3D printed four-marker rigid body attached to the transducers. Data from the B-mode images were recorded and synchronized with the motion capture system using the open-source software 3D Slicer (slicer.org; v. 4.10.1; Perth, Australia) (Fedorov et al.[17] Ungi et al.[18]). Two gel pads were used to avoid tissue compression and to improve ultrasound imaging quality.[19] The validity of freehand 3DUS to measure hamstring muscle and tendon volume has been established (see Bohm et al.[20]).

Participants were positioned in prone for scanning. Multiple sweeps (three–six) were undertaken to cover the entire muscle bulk moving the transducer from proximal (the ischial tuberosity) to distal insertions (the *pes anserinus* for the ST and SM, and the head of the fibula for the BF) in the transverse plane at a constant speed (~1 cm/s).[20] The distal tendon of ST was located distally with the *pes anserinus* (in association with *gracilis* and *sartorius*). Freehand 3DUS acquisition was stopped 6 cm distal to this musculotendinous junction. The same experimenter trained in ultrasound imaging performed all testing blinded to group allocation.

2.5 | Maximum voluntary torque

Unilateral maximal isometric knee flexion torque was measured at 80° of hip flexion and at 60° of knee flexion with an isokinetic dynamometer (ConTrex MJ, CMV AG, Dubendorf, Switzerland). Three maximal voluntary contraction (MVC) trials were performed. If more than 10% of variation was found between the MVCs, a fourth trial was performed. For MVC trials, participants were asked to generate maximal strength as fast and as strong as possible, and to maintain the contraction for 3–4 s. They were strongly encouraged by the experimenter. The MVCs were performed with 2 min of rest in between.

2.6 | Data processing

2.6.1 | Quantification of training load

As training volume is the main resistance training feature that influences muscle hypertrophy,[21,22] total training volume (TTV) was quantified as follows [Equation 1][23] and matched between HL and LL-BFR groups:

$$\text{TTV (a. u.)} = \text{nb. of sets} \times \text{nb. of reps.} \times \%\text{RM for RR} \quad (1)$$

Note that the % RM for relative range (RR) corresponded to the number of repetitions performed at a given load expressed as a percentage of the maximal number of repetitions. This method allowed us to consider the metabolic load of each set.[22]

2.6.2 | 3DUS imaging volume reconstruction

For each acquisition, the 3D volume reconstruction of the 2D ultrasound images was performed in the 3D Slicer application, using the module "volume reconstruction".[18] Accordingly, the reconstruction process was automatic for each volume (Figure 1). The algorithm used in 3D Slicer was the same as that used in PlusServer, that is, a 3D voxel array is filled with the pixels from the ultrasound images. The interpolation mode was set to "Linear," meaning that each pixel value was inserted into the spatially nearest set of 8 voxels using trilinear interpolation weights to insure the consistency of the 3D reconstructed image. The size of the voxel was set to 0.10*0.10 for the transverse direction and set to 1.00 mm for the longitudinal direction, for both muscles and tendons.

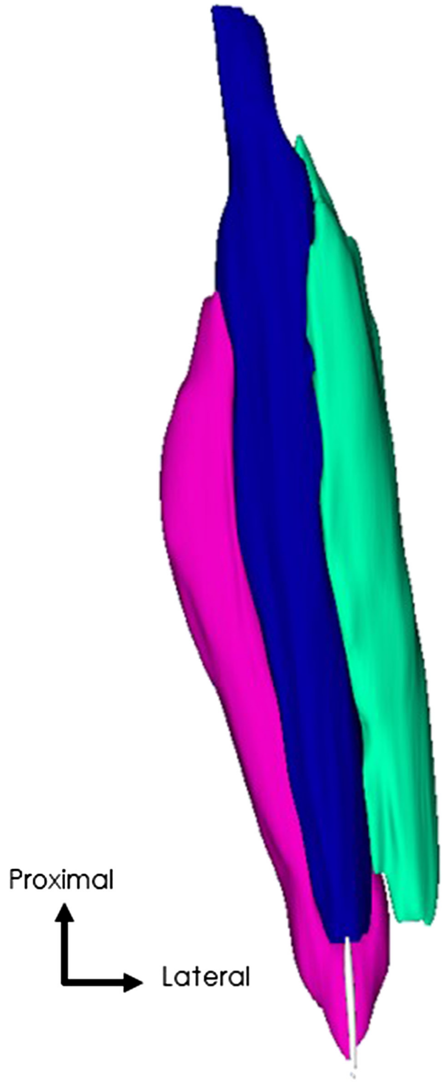

FIGURE 1 Typical 3D reconstruction of hamstring volume from 3D freehand ultrs. *Biceps femoris* long head is represented in green, *semitendinosus* in blue, and *semimembranosus* in pink.

2.6.3 | 3DUS imaging volume segmentation

Using 3D Slicer v. 4.10.1, manual segmentation was performed on each muscle and tendon by an experienced operator (Fedorov et al.[17]). Muscle boundaries were segmented every 7 mm from proximal to distal insertions, which corresponded to 50–55 slices for the different hamstring heads depending on the individual. From proximal to distal landmarks, tendon boundaries of ST were segmented every 3 mm, leading to a total of 40 slices. The operator was blinded from participant and session information.[21]

2.7 | Statistics

All statistical analyses were performed with Rstudio (Statistica v7.0, StatSoft, Tulsa, OK, USA). Paired t-test were performed to report differences between groups in anthropometric variables. A simple linear model was used to report the effect of group (between subject factor: LL-BFR, HL, and CON) on MVC or ST tendon volume. To consider the subject-specific differences, we used a linear mixed effect model to determine the influence of the group (LL-BFR, HL, and CON) on the relative changes in hamstring volume and muscle (SM, ST, and BF). When appropriate, a Bonferroni corrected *post hoc* analysis was performed. Effect sizes were calculated using Hedge's G for intra and between-group comparisons considering <0.1, 0.1–0.29, 0.30–0.49, >0.5 as *negligible*, *small*, *medium*, and *large* effect, respectively.[24] Level of significance was set at $p<0.05$.

3 | RESULTS

Participant characteristics are presented in Table 1. No significant differences in anthropometric features were detected between groups (all p-values >0.50). A total of 36 participants completed the 9 weeks training program (80% completion rate). All of the dropouts ($n=9$; HL (4), LL-BFR (2), and CON (3)) were for personal convenience and/or injuries from usual sport activities. The total training load did not significantly differ between LL-BFR (9923 ± 1131 a.u.) and HL (10 245 ± 1253 a.u.) ($p=0.389$) (Table 2).

3.1 | Maximum voluntary torque

There was a significant effect of group on MVC ($p=0.043$). The increase in MVC was greater in HL (9.5 ± 13.3%) compared to control group (−0.34 ± 8.75%) ($p=0.004$). No significant differences were found between LL-BFR (6.16 ± 9.28%) and CON ($p=0.314$), neither between LL-BFR and HL ($p=0.961$).

3.2 | Relative changes in muscle volume

A significant group*time interaction was detected ($p=0.015$).

3.2.1 | Biceps femoris long head

The change in BF was not different in LL-BFR (14.0 ± 16.5%), compared to CON ($p=0.436$). No difference was found neither between HL (4.0 ± 9.1%) and CON (1.1 ± 6.9%) ($p=1$), nor between HL and BFR ($p=1$) (Figure 2). Interindividual variability of the changes in muscle volume, attributable to training, is noteworthy. The largest hypertrophy within the hamstring group was found in the BF muscle for 38% of the LL-BFR participants (5/13), while this result was not observed in any participant of HL group (0/11) (Figure 3).

3.2.2 | *Semitendinosus*

The relative increase in ST volume compared to baseline was greater in HL (26.5 ± 25.5%) compared to CON ($p=0.004$, Figure 2B). No difference was found with LL-BFR (10.8 ± 11.4%) ($p=0.376$) (Figure 2B) neither between CON (−0.14 ± 7.29%) and LL-BFR ($p=0.627$). The hypertrophy of the ST muscle was largest within the hamstring group for 23% (3/13) and 73% (8/11) participants of LL-BFR and HL groups, respectively (Figure 3).

3.2.3 | *Semimembranosus*

The percentage change in SM volume was greater for LL-BFR (21.6 ± 27.8%) compared to CON (0.29 ± 5.19%) ($p=0.025$) but no difference was found with HL (17.1 ± 20.5%) ($p=1.0$) (Figure 2C). No difference was found between HL and CON ($p=0.178$). Moreover, 38% (5/13) and 27% (3/11) participants exhibited a largest hypertrophy of the SM in the LL-BFR and HL groups, respectively (Figure 3).

TABLE 1 Participants features for each group.

Group	HL	BFR-LL	CON
Women/Men	5/6	4/9	4/8
Age (years)	21.6 ± 3.1	21.6 ± 2.9	23.4 ± 4.0
Height (cm)	174.9 ± 8.8	175.0 ± 8.0	174.2 ± 10.9
Weight (kg)	69.4 ± 11.0	68.0 ± 8.9	68.4 ± 8.4

Abbreviations: BFR-LL, low load with blood flow restriction; CON, control; HL, high load.

TABLE 2 Total training load (a.u.) per exercise for each group.

Total training load (a.u.)			
Group	Seated leg curl	Stiff-leg deadlift	Total training load
BFR-LL	38 866	31 967	140 319
HL	41 003	28 318	139 792

Abbreviations: HL, high load; BFR-LL, low load with blood flow restriction.

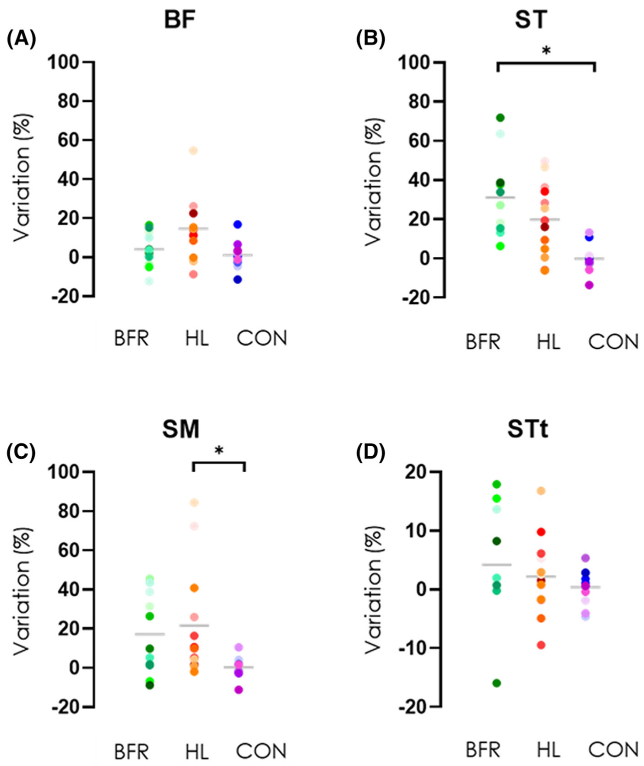

FIGURE 2 Muscle and tendon volume before (pre) and after (post) a 9-week resistance training program with high load (HL), and low load with blood flow restriction LL-BFR (BFR). The control group (CON) did not receive any intervention. (A) *Biceps femoris long head*; (B) *semitendinosus*; (C) *semimembranosus*; (D) *semitendinosus* tendon. Each participant is depicted by a colored circle that indicates individual variation. The gray line indicates the mean variation of each group. * indicates significant differences between pre and post measurements for each group ($p < 0.05$).

3.3 | Relative changes in tendon volume

Simple linear model revealed no significant effect of group for ST tendon ($p = 0.41$).

4 | DISCUSSION

The present study showed that the distribution of hypertrophy among the hamstring muscles differed between HL and LL-BFR groups. Although both groups trained with the same amount of hip-extension and knee-flexion movement, the HL program induced a selective hypertrophy of the ST muscle (26.5%), while no significant changes were found in SM (17.1%) and BF (4.0%) muscles compared to CON. In contrast, LL-BFR exhibited hypertrophy in SM (21.6%) but not for BF (14.6%) and ST (10.8%) muscles compared to CON. In addition, the magnitude of the selective hypertrophy observed within each group varied greatly between individuals. Regarding tendon, none of the training regimens induced significant hypertrophy of ST.

We found an increase of approximately +15.9% in whole hamstring muscle volume after a 9-week resistance training program (three times a week) with high loads (12-RM). This result is similar than reported in Bourne's study (12%, 10 weeks of training).[6] Similarly, Maeo et al.[12] reported hypertrophy of +12.5% with a moderate training load (from 50% to 70% of 1-RM) after a 12-week training program. To the best of our knowledge, the present study is the first to report that LL-BFR and HL training regimes increased hamstring muscle volume to a similar extent, and is in accordance with previous studies that used LL-BFR on knee extensors[25] and elbow flexors.[26] Although LL-BFR produced less mechanical tension due to lower load, various mechanisms may trigger muscle hypertrophy and increase in strength. It has been suggested that increased levels of metabolic stress, due to the alteration of the venous return, is the primary driving stimulus in the hypertrophy induced by low load.[27] Briefly, LL-BFR training stimulates Groups III and IV afferent fibers through the accumulation of metabolites (e.g., lactate and hydrogen ions) that decreases intramuscular pH within a hypoxic environment. It triggers a cascade of anabolic reactions promoting hypertrophy (i.e., angiogenesis, satellite cells activation, and increase in growth hormone).[27–29] This hypertrophy was associated with an increase in maximal knee flexion strength for HL (+9.5%) compared to CON group, while no differences where observed between HL and LL-BFR groups. Relatedly, a recent systematic review indicated that both strengthening methods could induce a similar hypertrophic response with larger maximal strength gains observed for HL groups.[9]

For the first time, differences in the distribution of hamstring hypertrophy between HL and LL-BFR are reported. Some studies have used HL resistance training

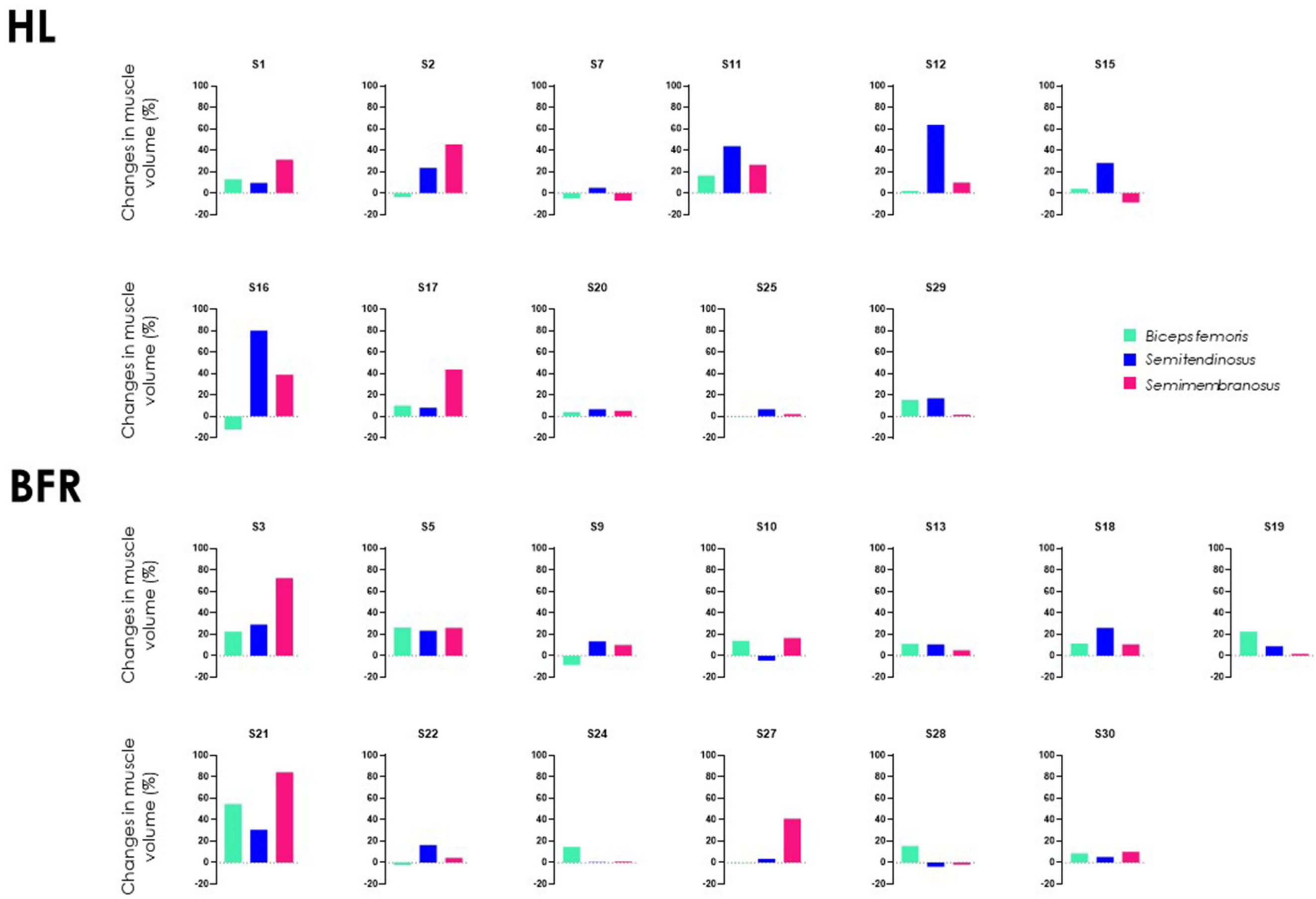

FIGURE 3 Hamstring volume variation as a percentage change for each participant after a 9-week resistance training for both groups (a = high load and b = low load with blood flow restriction). Each muscle is represented by a color: green = *biceps femoris* long head; blue = *semitendinosus*; pink = *semimembranosus*.

programs for inducing hamstring hypertrophy by either hip- or knee-dominant exercise.[6,12,30] We have collate the results from the different groups of these studies to estimate the distribution of hypertrophy induced by HL type programs composed of seated and lying leg curl,[12] Nordic hamstring,[12] 45° hip extension,[6] and hip extension (eccentric and isometric conditions[30]) exercises. This additional analysis on data of the literature showed a hypertrophy of approximately 18.5 ± 2.5% for ST, 7.1 ± 1.6% for SM, and 9.9 ± 0.8% for BF. This is in accordance with the current study showing a selective hypertrophy of the ST (+26.5 ± 25.5%). This largest hypertrophy of the ST was observed for 8 out of 11 participants of the HL group which is notably more than the 3 out of 13 participants in the LL-BFR group (Figure 3). This confirms that ST muscle exhibited a large hypertrophic potential when the individuals are involved in physical activities that require high force level, as previously shown on elite sprinters.[11] To the best of our knowledge, this is the first study reporting the distribution of hamstring hypertrophy after LL-BFR training program. Interestingly, LL-BFR induced a selective hypertrophy of the SM (21.6%). Although speculative, it is likely that the LL-BFR allows participants to choose a muscle coordination that limits the metabolic cost of the task[31] while it is not the possible for HL group, when a high level of force is required.[32,33] For a given muscle force, there will be less metabolic cost if the muscle with the greatest physiological cross sectional area (PCSA) is used.[31] As SM muscle exhibited the greatest PCSA (207 cm^3) compared to ST (173 cm^3) and BF (185 cm^3),[31] it is likely that the nervous system favored it contribution during the 9 weeks of training of the LL-BFR group. This bias of coordination to SM has been already reported at low level of force (20% of MVC),[34] close to those used in LL-BFR group (30% 1RM) of the present study. This bias of coordination was not observed at moderate level of force (~50% MVC).[34] Further research is needed to describe hamstring muscle coordination during such combination of exercises at HL and LL-BFR and its relationship with the distribution of muscle hypertrophy.

No previous studies have reported the interindividual variability in the distribution of the hypertrophy

(Figure 3). Regardless of the group, we found that the hypertrophy could be selective to ST (e.g., participant #12, Figure 3), BF (e.g., participant #19, Figure 3), SM (e.g., participant #27, Figure 3), or balanced (e.g., participant #5, Figure 3). Relatedly though, individual distribution of muscle activation (heterogenous activation between participants) has been observed during walking,[35] pedaling,[35] and resistance training exercises.[36] Such findings may explain, at least partly, the individual distribution of hypertrophy reported above. Although the distribution of muscle activation does not predict the distribution of hypertrophy,[32,37] a recent study from Goreau et al.[38] has shown that the distribution of activation has mechanical consequences. These authors considered the distribution of muscle damage, after an unaccustomed bout of maximal eccentric contractions, as a model to study distribution of mechanical stress among a muscle group. Interestingly, the authors reported that when considering an individual muscle, the larger the bias of activation to a muscle, the larger the amount of damage to this particular muscle. It is reasonable to assume that the repetition of this exercise over time, with this distribution of mechanical stress (related to the distribution of activation), may influence the distribution of hypertrophy among a muscle group. The estimation of individual muscle force using a forward dynamic approach[35] would be a relevant approach to test this hypothesis.

Numerous studies have shown that tendon (e.g., Achilles and patellar tendon) morphological adaptations can be influenced by the type of resistance training (for review see Ref. [20]). ST tendon is often chosen for ACL reconstruction surgery. In respect of this premise, we focused upon ST tendon hypertrophy. No significant tendon hypertrophy was observed (i.e., HL (4.2 ± 9.4%)), LL-BFR (1.9 ± 7.1%), and CON (0.4 ± 2.5%) ($p = 0.411$). This finding was not in accordance with previous studies showing significant hypertrophy in patellar and Achilles tendons.[9,13] However, it is important to note that although nonsignificant, the magnitude of the changes in tendon volume in LL-BFR ($g = 0.05$ (2.0%)) and the HL groups ($g = 0.18$ (4.2%)) observed in the current study were similar to those reported in the aforementioned studies. Malliaras et al.[8] reported an increase about approximately 5% in the patellar tendon after a 9-week HL (80% 1RM) resistance training program. Also, Centner et al.[9] reported an average increase in patellar tendon CSA about approximately 4% for both groups (HL and LL-BFR training) after 14 weeks of training. Two main hypotheses may explain the absence of significant effect in our study. First, the 9-week training period could be too shorter term to have induced a significant change in ST tendon volume. Second, some studies reported that the changes in patellar and Achilles tendon volume were heterogenous along their length.[9,13,39,40] Our approach at the level of tendon volume may have lacked of sensitivity to detect differences. Finally, the differences in baseline in tendon volume between subjects could have influenced the results of our study.

5 | PERSPECTIVES

Although LL-BFR and HL improved hamstring muscle volume to a similar extent, its distribution differed between SM, ST, and BF. The hypertrophy was mainly located in ST for the HL group while it was located in SM for the LL-BFR group, the magnitude of these distributions varied greatly between participants. These results provide the first impetus for trying to personalize rehabilitation exercise aiming to induce a selective hypertrophy. Regarding the selective atrophy reported after ACL reconstruction (Konrath et al.[41]) it could be interesting to determine whether tailored pre- and/or post-surgical rehabilitation programs enhance maximal strength restoration after an ACL repair. It is also relevant for any intervention that aimed at tailoring hypertrophy among hamstring muscles.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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