论著·军事医学

低负荷血流限制训练可作为高负荷离心训练的有效替代以改善跟腱性能:小腿方案为更优选择

樊竞远[1],李 婧[1],潘玮敏[1,2],张龙国[1],冯 欢[1],魏晓宇[3],黄 艳[1],蒋应鹏[4],刘 民[5] [1]西安体育学院运动与健康科学学院,陕西西安;[2]体育智能装备关键技术陕西省高校工程研究中心,陕西西安;[3]西安高新医院康复医学科,陕西西安;[4]山西省荣军医院康复医学科,山西太原;[5]空军军医大学西京医院骨科,陕西西安

[**摘要**] **目的** 对比两种不同的血流限制康复方案与经典高负荷离心抗阻训练(high-load eccentric resistance training,HL)对健康成年人跟腱形态及生物力学性能的影响,为军事训练中跟腱损伤的预防提供替代训练方案。**方法** 采用随机对照试验的研究方法,于2024年12月20-23日招募西安市某高校健康成年人55例,采用随机数字表法分为3组:高负荷离心抗阻训练组(HL组,n=18)、小腿血流限制结合低负荷离心抗阻训练(low-load eccentric resistance training with calf-applied blood flow restriction,C-BFR)组(n=16)和大腿血流限制结合低负荷离心抗阻训练(low-load eccentric resistance training with thigh-applied blood flow restriction,T-BFR)组(n=19),3组均完成8周训练方案,分别于干预前、6周、8周时采用彩色多普勒超声评估跟腱横截面积,采用彩色多普勒超声及无线肌肉测力计评估跟腱刚度、跟腱杨氏模量,同步采用无线肌肉测力计及表面肌电检测内侧腓肠肌最大自主等长收缩力(maximal voluntary isometric contraction,MVIC),采用三维测力台测量反向运动跳(counter movement jump,CMJ)跳跃高度及下落跳(drop jump,DJ)触地时间。**结果** 干预8周后,采用彩色多普勒超声评估跟腱横截面积,3组跟腱横截面积均较干预前显著增加(P<0.01,η^2=0.847),且C-BFR组增幅高于T-BFR组。干预8周后,采用彩色多普勒超声及无线肌肉测力计评估跟腱刚度、跟腱杨氏模量,3组跟腱刚度均较干预前显著增加(P<0.01,η^2=0.722),且C-BFR组增幅高于HL组与T-BFR组;T-BFR组跟腱杨氏模量较干预前差异无统计学意义(P>0.05),C-BFR组与HL组均较干预前显著增加(P<0.05,η^2=0.181),且C-BFR组增幅高于HL组与T-BFR组。干预8周后,采用无线肌肉测力计及表面肌电检测内侧腓肠肌MVIC,3组MVIC均较干预前显著增加(P<0.01,η^2=0.775),且C-BFR组增幅高于T-BFR组。干预8周后,采用三维测力台测量CMJ跳跃高度及DJ触地时间,3组CMJ跳跃高度均较干预前显著增加(P<0.01,η^2=0.569),且C-BFR组增幅高于T-BFR组;3组DJ触地时间均较干预前显著缩短(P<0.01,η^2=0.518),且C-BFR组缩短增幅高于T-BFR组。**结论** 两种不同的血流限制方案结合低负荷离心抗阻训练均可使跟腱形态、生物力学性能和运动学表现达到与经典高负荷离心抗阻训练相似的改善效果;且相较于T-BFR方案,C-BFR方案更具优势。

[**关键词**] 跟腱;血流限制训练;抗阻训练;生物力学;运动损伤

[**中图法分类号**] R364.12;R493;R686.109 [**文献标志码**] A

[**基金项目**] 陕西省自然科学基础研究计划面上项目(2021JM-530)

[**通信作者**] 潘玮敏,E-mail:panweimin@163.com

2097-0927/Copyright © 2026, 陆军军医大学(第三军医大学)。这篇开放获取文章遵循 CC BY 许可协议 (https://creativecommons.org/licenses/by/4.0/)

引用格式:樊竞远,李婧,潘玮敏,等. 低负荷血流限制训练可作为高负荷离心训练的有效替代以改善跟腱性能:小腿方案为更优选择[J]. 陆军军医大学学报,2026,48(04):470-478. DOI:10.16016/j.2097-0927.202511036.

Citation:FAN J Y,LI J,PAN W M,*et al*. Low-load blood flow restriction training as a viable alternative to high-load eccentric training for improving Achilles tendon properties: the superiority of a calf-specific regimen[J]. J Army Med Univ,2026,48(04):470-478. DOI:10.16016/j.2097-0927.202511036.

Low-load blood flow restriction training as a viable alternative to high-load eccentric training for improving Achilles tendon properties: the superiority of a calf-specific regimen

FAN Jingyuan[1], LI Jing[1], PAN Weimin[1,2], ZHANG Longguo[1], FENG Huan[1], WEI Xiaoyu[3], HUANG Yan[1], JIANG Yingpeng[4], LIU Min[5] [1]College of Sports and Health Sciences, Xi'an Physical Education University, Xi'an, Shaanxi; [2]Engineering Research Center of Innovative Technology of Intelligent Sports Equipment, Universities of Shaanxi Province, Xi'an, Shaanxi; [3]Department of Rehabilitation Medicine, Xi'an Gaoxin Hospital, Xi'an, Shaanxi; [4]Department of Rehabilitation Medicine, Shanxi Rongjun Hospital, Taiyuan, Shanxi; [5]Department of Orthopedics, Xijing Hospital, Air Force Medical University, Xi'an, Shaanxi, China

[**Abstract**] Objective To compare the effects of 2 different blood flow restriction (BFR) rehabilitation protocols versus classic high-load eccentric resistance training on the morphology and biomechanical properties of the Achilles tendon in healthy adults, and to provide alternative training strategies for preventing Achilles tendon injuries in military training. Methods A randomized controlled trial was conducted. Fifty-five healthy adults from a university in Xi'an were enrolled between December 20 and 23, 2024, and randomly assigned to one of three groups using a random number table: a high-load eccentric resistance training group (HL, n=18), a low-load eccentric resistance training with calf-applied BFR group (C-BFR, n=16), and a low-load eccentric resistance training with thigh-applied BFR group (T-BFR, n=19). All groups completed an 8-week training program. Achilles tendon cross-sectional area was assessed using color Doppler ultrasonography at baseline, 6 weeks and 8 weeks. Achilles tendon stiffness and Young's modulus were evaluated using color Doppler ultrasonography and a wireless microFET3 dynamometer. The maximal voluntary isometric contraction (MVIC) of the medial gastrocnemius was simultaneously measured using the wireless microFET3 and surface electromyography. Countermovement jump (CMJ) height and drop jump (DJ) ground contact time were measured using a three-dimensional force platform. Results After 8 weeks of intervention, color Doppler ultrasonography assessment revealed that the cross-sectional area of the Achilles tendon significantly increased in all three groups compared to baseline (P<0.01, η^2=0.847), with a greater increase in the C-BFR group than in the T-BFR group. Tendon stiffness significantly increased in all three groups compared to baseline (P<0.01, η^2=0.722), and the increase was greater in the C-BFR group than in the HL and T-BFR groups. For Young's modulus, no statistically significant change was observed in the T-BFR group compared to baseline (P>0.05), while both the C-BFR and HL groups showed significant increases (P<0.05, η^2=0.181), with a greater increase in the C-BFR group than in the HL and T-BFR groups. The MVIC of the medial gastrocnemius significantly increased in all three groups compared to baseline (P<0.01, η^2=0.775), with a greater increase in the C-BFR group than in the T-BFR group. CMJ height significantly increased in all three groups (P<0.01, η^2=0.569), with a greater increase in the C-BFR group than in the T-BFR group. DJ ground contact time significantly shortened in all three groups (P<0.01, η^2=0.518), and the shortening was greater in the C-BFR group than in the T-BFR group. Conclusion Both C-BFR and T-BFR combined with low-load eccentric resistance training can achieve improvements in Achilles tendon morphology, biomechanical properties, and kinematic performance similar to those achieved with classic high-load eccentric resistance training. Furthermore, compared to the T-BFR protocol, the C-BFR protocol demonstrates superior benefits.

[**Key words**] Achilles tendon; blood flow restriction training; resistance training; biomechanics; athletic injuries

Supported by the General Project of Natural Science Basic Research Plan of Shaanxi Province (2021JM-530). Corresponding author: PAN Weimin, E-mail: panweimin@163.com

跟腱作为人体最大的肌腱,主要功能是将小腿三头肌产生的力传递至跟骨结节以产生运动。然而,因其中段生理性较窄、血供较差,且在运动中承受较高机械应力(跑跳中可达体质量的8~10倍以上[1]),故易形成跟腱病且难以完全康复。流行病学研究显示,普通人群跟腱病发生率达5.9%,而在运动人群中则高达23.9%[2],军人为满足军事作战能力提升的需求,其日常训练强度及任务功能性要求高,跟腱病发病率也显著高于普通人群[3],且在发病机制和高发特征上与运动群体呈现一致性。跟腱病常表现为跟腱形态异常与生物力学性能下降[4],不仅造成日常活动的疼痛与不适,更会影响军人的训练效能、运动表现及作战能力[5],甚至引发跟腱断裂。因此,跟腱病的预防已成为康复医学领域的核心研究焦点之一。

离心抗阻训练作为跟腱病预防与康复的"金标准",其通过特定的抗阻负荷促进跟腱形态及生物力学性能的适应性改善,从而降低跟腱病罹患风险[6-7]。有研究证实,抗阻负荷达到一次最大重复力量(one repetition maximum,1RM)的70%以上时,方可显著促进跟腱形态及生物力学性能的积极改变[8],但伴随着更高的损伤风险。而低负荷抗阻训练(low-load resistance training,LL)虽可有效降低跟腱所受机械应力,降低损伤发生率,却无法有效引起跟腱的适应性变化[9]。因此,探究如何在LL下实现与高负荷离心抗阻训练(high-load eccentric resistance training,HL)相似的跟腱形态和生物力学适应效果,已成为对军人跟腱病预防和临床康复领域的核心研究方向。

血流限制(blood flow restriction,BFR)训练通过对肢体加压,减少动脉血液流入并阻塞静脉血液回流,提高训练和康复效果[10-11]。已有研究表明,LL-BFR训练可使健康成年人的跟腱产生适应性改变,其在形态及生物力学方面的适应效果,与HL训练所诱导的改变具有相似性[12],这些适应性变化能够有效降低跟腱病的罹患风险[13]。而当前BFR干预方案仍处于临床探索阶段,现有研究形成两种施加方案:其一为大腿近端施加50%的动脉闭塞压(arterial occlusion pressure,AOP)的压力[12,14],其二为小腿近端施加30%AOP的压力[3,15-16],两种施加方案均证实对跟腱产生积极影响。但压力施加部位的解剖形态差异可能影响到干预效果[17],且跟腱血供来源于腘动脉及其分支[18],两种方案可能通过影响局部代谢环境和力学刺激的不同,使得跟腱适应的效果存在差异。基于此,本研究探索性地将两种BFR方案与传统HL进行对比,分析其对跟腱形态及生物力学性能影响的差异,以期为军人日常训练中预防跟腱病提供理论基础及针对性方案,并推动其在跟腱病患者康复中的临床应用转化。

1 资料与方法

1.1 研究对象

于2024年12月20-23日在西安市某高校招募共55名受试者,开展随机对照试验。纳入标准:①年龄18~35岁;②无跟腱疼痛、跟腱损伤或下肢严重创伤病史;③无规律抗阻训练习惯;④自愿参与研究并签署知情同意书。排除标准:①有吸烟史、心血管及中枢神经系统疾病;②下肢患有深静脉血栓或血管病变等血流限制禁忌症;③下肢生物力学力线异常者;④研究期间服用可能影响结果的药物如喹诺酮类或皮质激素等[19]。充分告知本研究的具体内容和注意事项,要求受试者在此期间遵循正常饮食和睡眠,测试前48 h内禁止高强度体育活动。本研究经西安体育学院伦理委员会批准(XAIPE2024038),并于中国临床试验注册中心通过审核(ChiCTR2400094369)。所有受试者和结局指标评估者对试验分组和设计不知情。各组基线资料差异无统计学意义(表1)。

1.2 研究工具

LOGIQ Book XP彩色多普勒超声(美国GE Healthcare公司)、无线肌肉测力计(美国HOGGAN公司)、三维测力台(瑞士KISTLER公司)、无线遥感表面肌电测试仪(美国NORAXON公司)、心率遥测仪(芬

表1 3组受试者一般资料分析($\bar{x}\pm s$)

Table 1 General information of the 3 groups of participants ($\bar{x}\pm s$)

Group	n	Gender(M/F)	Age/years	Height/m	Weight/kg
C-BFR	16	12/4	20.75±2.82	1.71±0.10	65.56±11.06
HL	18	15/3	22.50±3.90	1.73±0.05	66.91±8.06
T-BFR	19	15/4	21.26±2.66	1.74±0.09	69.69±11.10
χ^2/F	0.264	0.359	1.387	0.508	0.760
P	0.876	0.836	0.259	0.605	0.473

兰Polar Electro公司)、血流加压训练带(中国河南健衡医疗公司)、康复器械史密斯机(美国Life Fitness公司)。

1.3 方法

采用随机对照试验的方法,样本量计算采用G Power 3.1,效应量0.3,显著性水平0.05,检验效能0.8[20],计算得到总样本量为39。考虑脱落情况及各组间等比性,最终筛选55例受试者,符合纳入、排除标准。将55名受试者按招募顺序编号,使用SPSS 27.0软件生成随机序列,采用随机数字表法将受试者分配至大腿血流限制结合低负荷离心抗阻训练(low-load eccentric resistance training with thigh-applied blood flow restriction, T-BFR)组、小腿血流限制结合低负荷离心抗阻训练(low-load eccentric resistance training with calf-applied blood flow restriction, C-BFR)组和高负荷离心抗阻训练组(HL组)。试验过程中C-BFR脱落2例,最终纳入53例,其中T-BFR组19例,C-BFR组16例,HL组18例,各组无不良事件发生,所有袖带滑移事件及时调整,未影响干预完成。

在正式干预前,所有受试者参加20 min的培训课程,接受口头指导和正确的技术示范,以充分熟悉并掌握离心训练技术。测试前1~2 d于温控试验室内采用LOGIQ Book XP彩色多普勒超声仪测定AOP,受试者休息10 min后,站立位下以袖带加压至胫后动脉脉搏消失时的压力记为100% AOP,重复测量3次,每次间隔10 min,取平均值作为个体AOP值。并采用Epley公式估算1RM:若成功完成5次以上重复,则负荷增加5%;若无法完成5次重复,则通过公式估算1RM[21]:$1RM = 负荷(kg) \times \left[1 + \left(0.03 \times 重复次数\right)\right]$,每次尝试间隔休息5 min。

每次训练前,进行5 min功率自行车热身,使用心率遥测仪监测运动强度,心率控制在Inbar公式预测的最大心率的60%[15]。全体受试者进行为期8周、每周3次的干预,每次干预持续15~20 min,相邻2次干预间隔至少24 h,以确保充分恢复。

1.3.1 HL方案 标准化热身后,受试者通过康复器械史密斯机增加负荷量,站立于倾斜台面上,按节拍器控制的节奏(向心收缩1 s、离心收缩2 s)完成足跟抬高后缓慢下落的全关节活动范围跖屈离心运动,过程中配合口头提示规范动作;训练先在伸膝位进行,依次完成以30%1RM为负荷的1组30次的离心抗阻和以70% 1RM为负荷的3组10次离心抗阻(组间休息30 s),休息1 min后换至屈膝位,以相同负荷、组数、次数及休息时间重复上述动作,且每2周通过重新测量1RM调整1次负荷。

1.3.2 C-BFR方案 标准化热身后,通过血流加压训练带以30% AOP的限制程度,于小腿腘横纹下进行加压。训练动作同HL组,依次完成以30%1RM为负荷的1组30次的离心抗阻和以30% 1RM为负荷的3组15次的离心抗阻(组间休息30 s),袖带放气休息1 min后换至屈膝位,以相同负荷、组数、次数及休息时间重复上述动作,且每2周通过重新测量1RM调整1次负荷。

1.3.3 T-BFR方案 标准化热身后,通过血流加压训练带以50% AOP的限制程度,在大腿近端腹股沟下方进行加压,训练内容同C-BFR组。

1.4 测量指标

1.4.1 跟腱横截面积 采用LOGIQ Book XP彩色多普勒超声仪进行测量,受试者俯卧位,踝关节悬于治疗床末端并保持中立位。均匀涂抹耦合剂后使用7.5 MHz探头定位。跟腱横截面积统一于内踝水平(距跟骨结节上约4 cm处),采集3张清晰图像,取平均值。

1.4.2 跟腱刚度与跟腱杨氏模量 跟腱刚度由力-长度曲线得出,采用无线肌肉测力计测量受试者的跖屈肌力,换算得出跟腱力[22],同时使用彩色多普勒超声测量腓肠肌内侧肌肉收缩和舒张时的长度变化量。跟腱杨氏模量由应力-应变曲线的斜率得出,其中跟腱应力为单位横截面积上的力,跟腱应变为跟腱长度变化量与初长度的比值。

1.4.3 腓肠肌最大自主等长收缩力(maximal voluntary isometric contraction, MVIC) 采用无线遥感表面肌电测试仪和无线肌肉测力计测量受试者腓肠肌MVIC。进行局部皮肤毛发清理,酒精消毒,将电极片平行于肌纤维走向贴于腓肠肌内侧的肌腹膨隆处,所有电极由同一研究人员放置,并使用医用胶布固定。在测量受试者跟腱长度变化量的同时进行肌电数据记录,重复3次最大自主等长收缩,持续6 s。选择中间2 s的肌电信号计算MVIC,取平均值。

1.4.4 运动学表现 采用Kistler三维测力台进行测量。测量反向运动跳(counter movement jump, CMJ)最大跳跃高度;下落跳(drop jump, DJ)测试,受试者于40 cm的跳台跳下,通过地面反作用力曲线确定地面接触时间。2项测试均进行3次,并取平均值。

1.5 统计学分析

采用SPSS 27.0软件对所得数据进行统计学分析处理。采用Kolmogorov-Smirnov对3组的跟腱横截面积、跟腱刚度、跟腱杨氏模量、内侧腓肠肌MVIC、CMJ

跳跃高度及DJ触地时间进行正态分布检验,计量资料均符合正态分布,以$\bar{x}\pm s$进行描述,采用重复测量方差分析通过Mauchly Test判断是否符合球形假设,若不符合,使用Greenhouse-Geisser correction进行校正,两两比较采用LSD法,显著性水平α=0.05。

2 结果

2.1 跟腱横截面积增加

采用彩色多普勒超声测量跟腱横截面积。干预前,各组跟腱横截面积大小基线差异均无统计学意义。干预8周后,T-BFR、C-BFR与HL组跟腱横截面积均明显增加(P<0.01);组间比较,3组间差异无统计学意义(表2)。提示3组均有效改善跟腱横截面积。

2.2 跟腱刚度、杨氏模量增加

采用无线肌肉测力计和彩色多普勒超声测量跟腱刚度。干预前,各组跟腱刚度基线差异均无统计学意义。干预8周后,T-BFR、C-BFR与HL组跟腱刚度均明显增加(P<0.01);组间比较,3组间差异无统计学意义(表3),提示3组均有效改善跟腱刚度。

采用无线肌肉测力计和彩色多普勒超声测量跟腱杨氏模量。干预前,各组跟腱杨氏模量基线差异均无统计学意义。干预8周后,T-BFR组跟腱杨氏模量增长未达到显著性水平(P>0.05),C-BFR与HL组跟腱杨氏模量的增加有显著性(P<0.05);组间比较,3组间差异无统计学意义(表3)。提示C-BFR与HL均能有效改善跟腱杨氏模量,并优于T-BFR。

2.3 内侧腓肠肌MVIC增加

采用无线肌肉测力计和无线遥感表面肌电测试仪测量腓肠肌MVIC。干预前,各组内侧腓肠肌MVIC基线差异均无统计学意义。干预8周后,T-BFR、C-BFR与HL组内侧腓肠肌MVIC均明显增加(P<0.01);组间比较,3组间差异无统计学意义(表4)。提示3组均有效增加内侧腓肠肌MVIC。

2.4 CMJ跳跃高度增加、DJ触地时间降低

采用Kistler三维测力台测量CMJ跳跃高度。干预前,各组CMJ跳跃高度基线差异均无统计学意义。干预8周后,T-BFR、C-BFR与HL组跳跃高度均明显增加(P<0.01);组间比较,3组间差异无统计学意义(表5)。提示3组均有效增加CMJ跳跃高度。

采用Kistler三维测力台测量DJ触地时间。干预前,各组DJ触地时间基线差异均无统计学意义。干预8周后,T-BFR、C-BFR与HL组触地时间均明显降低(P<0.01);组间比较,3组间差异无统计学意义(表5)。提示3组均有效降低触地时间。

表2 3组干预前后跟腱横截面积变化的比较($\bar{x}\pm s$)

Table 2 Comparison of changes in Achilles tendon cross-sectional area among 3 groups pre- and post-intervention ($\bar{x}\pm s$)

Outcomes	Time point	HL(n=18)	C-BFR(n=16)	T-BFR(n=19)	P			η^2		
					B	W	G	B	W	G
Achilles tendon cross-sectional area /cm^2	Baseline	0.465±0.070	0.448±0.076	0.483±0.061	0.140	<0.001	0.331	0.076	0.847	0.045
	6 week	0.558±0.054[a]	0.522±0.068[a]	0.573±0.078[a]						
	8 week	0.611±0.046[a]	0.570±0.072[a]	0.603±0.068[a]						

a: P<0.01, compared with baseline; B: between-group main effect; W: within-group main effect; G: group×time interaction effect

表3 3组干预前后跟腱刚度、杨氏模量变化的比较($\bar{x}\pm s$)

Table 3 Comparison of changes in Achilles tendon stiffness and Young's modulus among 3 groups pre- and post-intervention ($\bar{x}\pm s$)

Outcomes	Time point	HL(n=18)	C-BFR(n=16)	T-BFR(n=19)	P			η^2		
					B	W	G	B	W	G
Achilles tendon stiffness/(N/mm)	Baseline	239.768±54.624	253.220±58.930	262.254±73.768	0.399	<0.001	0.672	0.036	0.722	0.023
	6 week	287.926±60.098[b]	317.556±63.409[b]	320.536±87.769[b]						
	8 week	328.671±51.407[b]	359.995±71.920[b]	352.852±88.030[b]						
Young's modulus/MPa	Baseline	1 092.956±316.477	1 209.336±336.405	1 192.356±463.433	0.582	<0.001	0.860	0.021	0.181	0.013
	6 week	1 148.639±338.739	1 279.908±286.680	1 245.759±501.742						
	8 week	1 224.938±250.212[a]	1 367.143±350.625[a]	1 280.631±495.341						

a: P<0.05, b: P<0.01, compared with baseline; B: between-group main effect; W: within-group main effect; G: group×time interaction effect

表4 3组干预前后内侧腓肠肌MVIC变化的比较($\bar{x}\pm s$)

Table 4 Comparison of changes in MVIC of medial gastrocnemius among 3 groups pre- and post-intervention ($\bar{x}\pm s$)

Outcomes	Time point	HL(n=18)	C-BFR(n=16)	T-BFR(n=19)	P			η^2		
					B	W	G	B	W	G
MVIC of medial gastrocnemius /N	baseline	233.243±32.531	229.419±32.832	237.563±35.219	0.917	<0.001	0.814	0.003	0.775	0.015
	6 week	284.083±25.963[a]	287.500±25.157[a]	290.763±44.404[a]						
	8 week	321.353±30.822[a]	325.494±17.607[a]	320.111±27.236[a]						

a: P<0.01, compared with baseline; B: between-group main effect; W: within-group main effect; G: group×time interaction effect

表5 3组干预前后CMJ跳跃高度、DJ触地时间变化的比较($\bar{x}\pm s$)

Table 5 Comparison of changes in CMJ height and DJ ground contact time among 3 groups pre- and post-intervention ($\bar{x}\pm s$)

Outcomes	Time point	HL(n=18)	C-BFR(n=16)	T-BFR(n=19)	P			η^2		
					B	W	G	B	W	G
CMJ height /m	baseline	0.270±0.083	0.295±0.117	0.303±0.113	0.815	<0.001	0.343	0.008	0.569	0.044
	6 week	0.314±0.079[b]	0.333±0.118[b]	0.325±0.122[a]						
	8 week	0.344±0.080[b]	0.364±0.131[b]	0.353±0.116[b]						
DJ ground contact time/s	baseline	0.480±0.056	0.475±0.089	0.442±0.091	0.319	<0.001	0.089	0.045	0.518	0.077
	6 week	0.442±0.064[a]	0.392±0.068[b]	0.415±0.078						
	8 week	0.393±0.063[b]	0.380±0.072[b]	0.360±0.091[b]						

a: P<0.05, b: P<0.01, compared with baseline; B: between-group main effect; W: within-group main effect; G: group×time interaction effect

3 讨论

跟腱作为传递力的组织,其适应性重塑需要时间的累积效应。本研究通过对比两种BFR施加方案对健康成年人跟腱的影响,结果显示,3组受试对象的跟腱形态、生物力学性能[7]和运动学指标[23-25]均显著改善,这些适应性变化为长期执行高强度任务的军人群体跟腱病预防和临床康复提供了有力的试验证据。

3.1 3种干预方式对跟腱形态学变化的影响

本研究发现,HL可有效促进跟腱形态适应性变化,这与既往研究结果一致[9,26]。同时,干预8周后,C-BFR和T-BFR在改善跟腱横截面积方面与HL差异无统计学意义,这与既往认为LL难以引起跟腱适应性改变的观点不同。基于国内外BFR相关研究的基础,本研究推测LL-BFR并非主要依靠力学刺激,其可能通过加压营造局部缺血缺氧环境,激活缺氧诱导因子-1α[27-28]、雷帕霉素靶标蛋白等信号通路[29-30],促进血管内皮生长因子等细胞因子释放[28,31-32],从而增强肌腱干细胞的增殖与胶原合成[33],改善跟腱血供与营养,最终实现跟腱横截面积的生理性增加。其中C-BFR组的跟腱横截面积增长率高于T-BFR组,这可能与小腿部位的精准施压密不可分。解剖上,跟腱血供来源于胫后动脉(近端为腘动脉)[18],C-BFR组通过对跟腱供血血管实施更直接、精确的血流限制,从而增强了BFR的干预效应。

3.2 3种干预方式对跟腱生物力学性能变化的影响

跟腱刚度的提升有利于力量传递、提高运动表现,并通过减少应变程度降低损伤风险[8,23]。本研究中3组干预后跟腱刚度均显著性增加,且两种LL-BFR方案与HL在提升跟腱刚度方面效果相似。跟腱刚度与其几何形态密切相关,尽管C-BFR采用更低的闭塞压力,但其刚度增长率仍高于T-BFR,再次证实BFR的施压部位可能是促进跟腱适应性变化的关键因素。不同于跟腱刚度的变化趋势,跟腱杨氏模量在干预6周后,3组较干预前均差异无统计学意义,而干预8周后仅HL与C-BFR较干预前显著提高,且C-BFR增长率高于T-BFR。杨氏模量主要反映跟腱自身固有的材料性质[8],其变化主要与跟腱组织内Ⅰ型胶原的含量、胶原纤维间的排列和交联形式、水分含量等因素相关。综上,3组跟腱刚度早期提升主要源于其横截面积的增加,经过更长时间的积累跟腱才通过材料性质的适应性变化促进杨氏模量提升,又进一步促进了刚度的提升。这一变化规律与RADOVANOVIĆ等[7]的研究结果相似,其通过对跟腱病患者进行12周经典

Alfredson离心抗阻和高负荷康复训练,发现跟腱形态和刚度的显著性变化出现时间更早,而杨氏模量的变化则较晚。T-BFR干预8周后杨氏模量较干预前虽然增加,但差异无统计学意义。推测T-BFR跟腱组织中胶原纤维含量及结构的适应性变化可能滞后于HL与C-BFR,这或许与其干预施加方式导致跟腱自身材料性质的改变需更长时间累积有关[34],提示跟腱组织材料层面的适应性变化可能需要8周以上的时间[8, 35]。相比于T-BFR,HL的高负荷刺激与C-BFR更精准地局部施压,能更有效地诱发跟腱胶原重塑的积极变化,从而更早实现杨氏模量的显著提升。

3.3 3种干预方式对跟腱运动学表现变化的影响

运动学表现的CMJ与DJ间接反映跟腱刚度和功能状态,内侧腓肠肌MVIC则反映肌腱-肌肉单位在力学作用下的协同响应,经过适宜训练或康复干预调控的跟腱,力学传递效率得到提升,常表现为CMJ较高的跳跃高度[36]和DJ较短的触地时间[37]。本研究3组CMJ跳跃高度均显著提高,HL增长率大于C-BFR和T-BFR,这与跟腱刚度、杨氏模量增长趋势一致。CMJ中踝关节跖屈-背屈环节与离心训练的动作模式高度契合,进一步反映干预方案对运动学表现提升的一致性。此外,3组DJ触地时间均显著缩短,且C-BFR降幅大于T-BFR和HL,进一步证实跟腱生物力学性能的提升可有效优化运动表现,且C-BFR方案显示出更优的功能改善潜力。同时,3组内侧腓肠肌MVIC在干预后均显著提升,提示3种方案均能有效改善神经肌肉系统整体激活效果。本研究推测,C-BFR通过对小腿精确施压增强肌内代谢应激,激活更多Ⅱ型运动单位,使得腓肠肌进行更强的收缩反应[3],不仅缩短了DJ触地时间,更反映出跟腱储存弹性势能与释放效率的改善,以及神经肌肉激活水平的提升[38]。

本研究仍存在一定局限性:①尽管本研究为观察跟腱适应性变化的具体时序特征设置了3个时间点测量,结果发现,跟腱杨氏模量的变化滞后于其余指标,未来需延长干预时长并设置多时间点观测,明确跟腱材料结构适应性变化的具体时间节点,尤其需针对军人训练周期优化干预时序;②虽然BFR营造的缺血环境与离心训练所致的血流中断存在相似性,提示其或可作为跟腱病患者的康复方案,然而本研究作为探索性研究并未覆盖跟腱病患者,缺乏临床转化证据。

综上所述,C-BFR与T-BFR均能实现与HL相似的跟腱适应性变化;尽管干预8周后两组组间差异并无统计学意义,但C-BFR相比于T-BFR在各指标中均呈现出更好的改善趋势。此外,试验实施中发现大腿其锥形解剖结构易导致袖带滑移[17],研究中T-BFR滑移率远高于C-BFR,不仅影响干预效果稳定性,又降低了受试者训练积极性和依从性。而小腿围度及血管内径较小,适当降低加压强度提高了舒适度的同时更精准地提升了预防效果。因此,基于良好的干预效果和操作可行性,C-BFR更适合作为未来跟腱病预防的推荐方案,其核心机制与跟腱损伤、跟腱病患者的病理修复需求存在共性,为后续临床转化提供了方向,尤其对高频参与高强度训练的军人群体,可作为军事训练、预防伤病的补充方案。

利益冲突 本文所有作者声明不存在利益冲突

参考文献:

[1] REITER A J, MARTIN J A, KNURR K A, *et al*. Achilles tendon loading during running estimated *via* shear wave tensiometry: a step toward wearable kinetic analysis[J]. Med Sci Sports Exerc, 2024, 56(6): 1077-1084. DOI: 10.1249/MSS.0000000000003396.

[2] MILLAR N L, SILBERNAGEL K G, THORBORG K, *et al*. Tendinopathy[J]. Nat Rev Dis Primers, 2021, 7: 1. DOI: 10.1038/s41572-020-00234-1.

[3] 李婧, 潘玮敏, 樊竞远, 等. 血流限制下跑步热身对篮球运动员跟腱形态及功能急性的影响[J]. 陆军军医大学学报, 2025, 47(18): 2154-2162. DOI: 10.16016/j.2097-0927.202505013.
LI J, PAN W M, FAN J Y, *et al*. Acute effects of blood flow restriction running warm-up on achilles tendon morphology and function in basketball athletes[J]. J Army Med Univ, 2025, 47(18): 2154-2162. DOI: 10.16016/j. 2097-0927.202505013.

[4] SCOTT A, SQUIER K, ALFREDSON H, *et al*. ICON 2019: international scientific tendinopathy symposium consensus: clinical terminology[J]. Br J Sports Med, 2020, 54(5): 260-262. DOI: 10.1136/bjsports-2019-100885.

[5] ARYA S, KULIG K. Tendinopathy alters mechanical and material properties of the Achilles tendon[J]. J Appl Physiol, 2010, 108(3): 670-675. DOI: 10.1152/japplphysiol. 00259.2009.

[6] 杨金娟, 谢敏豪, 黄伟平, 等. 运动性肌腱损伤研究进展[J]. 中国运动医学杂志, 2019, 38(9): 809-815. DOI: 10.3969/j.issn.1000-6710.2019.09.012.
YANG J J, XIE M H, HUANG W P, *et al*. Research progress of sports tendon injury[J]. Chin J Phys Med, 2019, 38(9): 809-815. DOI: 10.3969/j. issn. 1000-6710.2019.09.012.

[7] RADOVANOVIĆ G, BOHM S, PEPER K K, *et al*. Evidence-based high-loading tendon exercise for 12 weeks leads to

increased tendon stiffness and cross-sectional area in achilles tendinopathy: a controlled clinical trial [J]. Sports Med Open, 2022, 8(1): 149. DOI:10.1186/s40798-022-00545-5.

[8] LAZARCZUK S L, MANIAR N, OPAR D A, *et al*. Mechanical, material and morphological adaptations of healthy lower limb tendons to mechanical loading: a systematic review and meta-analysis [J]. Sports Med, 2022, 52(10): 2405-2429. DOI:10.1007/s40279-022-01695-y.

[9] ARAMPATZIS A, KARAMANIDIS K, ALBRACHT K. Adaptational responses of the human Achilles tendon by modulation of the applied cyclic strain magnitude [J]. J Exp Biol, 2007, 210 (Pt 15): 2743-2753. DOI: 10.1242/jeb.003814.

[10] LOENNEKE J P, HAMMERT W B, KATAOKA R, *et al*. Twenty-five years of blood flow restriction training: what we know, what we don't, and where to next? [J]. J Sports Sci, 2025, 43(19): 2115-2132. DOI:10.1080/02640414. 2025.2474329.

[11] 王越, 杨亚萌, 常乐, 等. 两种不同血流限制训练对军校学员上肢肌肉即时效应的影响[J]. 陆军军医大学学报, 2023, 45(22): 2343-2351. DOI: 10.16016/j. 2097-0927.202303123.
WANG Y, YANG Y M, CHANG L, *et al*. Immediate efficacy of 2 types of blood flow restriction training on upper limb muscles in military cadets [J]. J Army Med Univ, 2023, 45(22): 2343-2351. DOI: 10.16016/j. 2097-0927.202303123.

[12] CENTNER C, LAUBER B, SEYNNES O R, *et al*. Low-load blood flow restriction training induces similar morphological and mechanical achilles tendon adaptations compared with high-load resistance training [J]. J Appl Physiol, 2019, 127 (6): 1660-1667. DOI: 10.1152/japplphysiol.00602.2019.

[13] JERGER S, CENTNER C, LAUBER B, *et al*. Effects of specific collagen peptide supplementation combined with resistance training on Achilles tendon properties [J]. Scand J Med Sci Sports, 2022, 32(7): 1131-1141. DOI: 10.1111/sms.14164.

[14] CENTNER C, JERGER S, LAUBER B, *et al*. Similar patterns of tendon regional hypertrophy after low-load blood flow restriction and high-load resistance training [J]. Scand J Med Sci Sports, 2023, 33(6): 848-856. DOI: 10.1111/sms.14321.

[15] CHULVI-MEDRANO I, PICÓN-MARTÍNEZ M, CORTELL-TORMO J M, *et al*. Different time course of recovery in Achilles tendon thickness after low-load resistance training with and without blood flow restriction [J]. J Sport Rehabil, 2020, 30 (2): 300-305. DOI: 10.1123/jsr.2019-0403.

[16] PICÓN-MARTÍNEZ M, CHULVI-MEDRANO I, CORTELL-TORMO J M, *et al*. Acute effects of resistance training with blood flow restriction on Achilles tendon thickness [J]. J Hum Kinet, 2021, 78: 101-109. DOI: 10.2478/hukin-2021-0032.

[17] ROLNICK N, KIMBRELL K, DE QUEIROS V. Beneath the cuff: Often overlooked and under-reported blood flow restriction device features and their potential impact on practice-a review of the current state of the research [J]. Front Physiol, 2023, 14: 1089065. DOI: 10.3389/fphys.2023.1089065.

[18] CHEN T M, ROZEN W M, PAN W R, *et al*. The arterial anatomy of the Achilles tendon: anatomical study and clinical implications [J]. Clin Anat, 2009, 22(3): 377-385. DOI:10.1002/ca.20758.

[19] TENG Z L, CAO S X, MA X, *et al*. Epidemiological characteristics of patients operated for Achilles tendon rupture in Shanghai [J]. Orthop Surg, 2022, 14(8): 1649-1655. DOI:10.1111/os.13347.

[20] CENTNER C, JERGER S, LAUBER B, *et al*. Low-load blood flow restriction and high-load resistance training induce comparable changes in patellar tendon properties [J]. Med Sci Sports Exerc, 2022, 54 (4): 582-589. DOI: 10.1249/MSS.0000000000002824.

[21] NICKERSON B S, WILLIAMS T D, SNARR R L, *et al*. Evaluation of load-velocity relationships and repetitions-to-failure equations in the presence of male and female spotters [J]. J Strength Cond Res, 2020, 34(9): 2427-2433. DOI: 10.1519/JSC.0000000000003731.

[22] 沈勇伟, 张林, 刘劲松. 短跑训练对跟腱横截面积和弹性模量的影响[J]. 体育学刊, 2010, 17(1): 92-95. DOI:10.16237/j.cnki.cn44-1404/g8.2010.01.020.
SHEN Y W, ZHANG L, LIU J S. Effects of sprint training on the cross-sectional area and modulus of elasticity of the Achilles tendon [J]. J Phys Educ, 2010, 17(1): 92-95. DOI:10.16237/j.cnki.cn44-1404/g8.2010.01.020.

[23] 张希妮, 王俊清, 傅维杰. 跟腱运动功能与生物力学特征的研究进展[J]. 医用生物力学, 2019, 34(1): 103-109. DOI:10.16156/j.1004-7220.2019.01.016.
ZHANG X N, WANG J Q, FU W J. Research advancements in motor function and biomechanical characteristics of Achilles tendon [J]. J Med Biomech, 2019, 34(1): 103-109. DOI: 10.16156/j.1004-7220.2019.01.016.

[24] 邓力勤, 张希妮, 肖松林, 等. 内侧腓肠肌-跟腱复合体形态学和力学特性的性别差异研究[J]. 应用力学学报, 2022, 39(2): 218-223. DOI: 10.11776/j.issn.1000-4939.

2022.02.003.
DENG L Q, ZHANG X N, XIAO S L, *et al*. Differences in morphological and mechanical properties of medial gastrocnemius-Achilles tendon unit between males and females[J]. Chin J Appl Mech, 2022, 39(2): 218-223. DOI:10.11776/j.issn.1000-4939.2022.02.003.

[25] MIYASAKA H, EBIHARA B, FUKAYA T, *et al*. Relationship between the Young's modulus of the Achilles tendon and ankle dorsiflexion angle at maximum squat depth in healthy young males[J]. Medicina, 2023, 59(6): 1105. DOI:10.3390/medicina59061105.

[26] GLASGOW P, PHILLIPS N, BLEAKLEY C. Optimal loading: key variables and mechanisms[J]. Br J Sports Med, 2015, 49(5): 278-279. DOI:10.1136/bjsports-2014-094443.

[27] CHRISTIANSEN D, BISHOP D J. Aerobic-interval exercise with blood flow restriction potentiates early markers of metabolic health in man[J]. Acta Physiol, 2022, 234(2): e13769. DOI:10.1111/apha.13769.

[28] SHAHID H, MORYA V K, OH J U, *et al*. Hypoxia-inducible factor and oxidative stress in tendon degeneration: a molecular perspective[J]. Antioxidants, 2024, 13(1): 86. DOI:10.3390/antiox13010086.

[29] HE Y W, LU S H, CHEN W B, *et al*. Exosomes derived from tendon stem/progenitor cells enhance tendon-bone interface healing after rotator cuff repair in a rat model[J]. Bioact Mater, 2024, 40: 484-502. DOI: 10.1016/j.bioactmat.2024.06.014.

[30] JIANG Y X, LIU T S, DUAN Z G, *et al*. A hydrated fibrous gene patch codelivers TGF-β1 siRNA/TAT and berberine for the treatment of peritendinous antiadhesion [J]. Acta Biomater, 2025, 203: 277-290. DOI: 10.1016/j. actbio. 2025. 07.014.

[31] MACHEK S B, HARRIS D R, ZAWIEJA E E, *et al*. The impacts of combined blood flow restriction training and betaine supplementation on one-leg press muscular endurance, exercise-associated lactate concentrations, serum metabolic biomarkers, and hypoxia-inducible factor-1α gene expression[J]. Nutrients, 2022, 14(23): 5040. DOI:10.3390/nu14235040.

[32] PATTERSON S D, LEGGATE M, NIMMO M A, *et al*. Circulating hormone and cytokine response to low-load resistance training with blood flow restriction in older men [J]. Eur J Appl Physiol, 2013, 113(3): 713-719. DOI: 10.1007/s00421-012-2479-5.

[33] RHATOMY S, UTOMO D N, PRAKOESWA C R S, *et al*. Ligament/tendon culture under hypoxic conditions: a systematic review[J]. Adv Pharm Bull, 2021, 11(4): 595-600. DOI:10.34172/apb.2021.069.

[34] BATES M E, TROOP L, BROWN M E, *et al*. Temporal application of lysyl oxidase during hierarchical collagen fiber formation differentially effects tissue mechanics [J]. Acta Biomater, 2023, 160: 98-111. DOI: 10.1016/j.actbio.2023.02.024.

[35] GEREMIA J M, BARONI B M, BOBBERT M F, *et al*. Effects of high loading by eccentric triceps surae training on Achilles tendon properties in humans [J]. Eur J Appl Physiol, 2018, 118(8): 1725-1736. DOI:10.1007/s00421-018-3904-1.

[36] WDOWSKI M M, ROSICKA K, HILL M. Influence of lower-limb muscular and tendon mechanical properties and strength on countermovement jump performance[J]. J Sports Med Phys Fitness, 2023, 63(1): 16-22. DOI: 10.23736/S0022-4707.22.13567-X.

[37] ABDELSATTAR M, KONRAD A, TILP M. Relationship between Achilles tendon stiffness and ground contact time during drop jumps[J]. J Sports Sci Med, 2018, 17(2): 223-228.

[38] 梁馨文, 韩亚兵, 王世林, 等. 血流限制下低强度增强式跳跃训练干预功能性踝关节不稳的效果[J]. 中国康复理论与实践, 2024, 30(3): 352-361. DOI: 10.3969/j.issn.1006-9771.2024.03.014.
LIANG X W, HAN Y B, WANG S L, *et al*. Effect of blood flow restriction combined with low-intensity plyometric jump training on functional ankle instabil-ity[J]. Chin J Rehabil Theory Pract, 2024, 30(3): 352-361. DOI:10.3969/j.issn.1006-9771.2024.03.014.

(**收稿**:2025-11-07;**修回**:2026-01-12)
(编辑 邓强庭)