DOI: 10.16835/j.cnki.1000-9817.2025359

·综 述·

运动对孤独症谱系障碍儿童肠道菌群影响的研究进展

潘祥[1,2,3],高艺博[1,2],江露沛[1,2],陈潇潇[1,4],王艺蓓[1],赵德强[1],张彦峰[1]

1.国家体育总局体育科学研究所,北京 100061;2.日本顺天堂大学运动健康科学研究科;
3.日本顺天堂大学运动健康医科学推进机构;4.锦州医科大学体育与运动康复学院

【摘要】 为了解运动对孤独症谱系障碍(ASD)儿童肠道菌群(GM)的影响,研究综述了运动调控 GM 的三大核心生物学通路:通过修复肠道屏障完整性,抑制脂多糖介导的神经炎症;通过优化短链脂肪酸等关键代谢产物,重塑肠脑对话;通过协同调节色氨酸-犬尿氨酸代谢通路与迷走神经信号通路,优化神经递质平衡。相互关联的通路不仅能缓解胃肠道不适,还能为改善 ASD 的核心行为症状(如社交缺陷和重复行为)提供坚实的生物学基础。未来研究需聚焦于建立标准化的运动干预方案,并采用多组学方法验证上述关键生物学通路的有效性,探索联合干预策略,从而为 ASD 儿童的精准干预提供更坚实的科学依据。

【关键词】 运动活动;孤独性障碍;胃肠道;细菌;儿童

【中图分类号】 G 806 R 748 B 844.1 R 378 【文献标识码】 A 【文章编号】 1000-9817(2025)12-1815-06

Research progress on the effects of exercise on gut microbiota among children with autism spectrum disorder

PAN Xiang, GAO Yibo, JIANG Lupei, CHEN Xiaoxiao, WANG Yibei, ZHAO Deqiang, ZHANG Yanfeng

China Institute of Sport Science, Beijing 100061, *China*

【**Abstract**】 To investigate the effects of exercise on gut microbiota(GM) among children with autism spectrum disorder(ASD), the review provides an in-depth summary of the three core biological pathways through which exercise modulates the GM: repairing the integrity of the intestinal barrier to inhibit lipopolysaccharide-mediated neuroinflammation; optimizing key metabolites, such as short-chain fatty acids, to reshape gut-brain communication; synergistically regulating the tryptophan-kynurenine metabolic pathway and vagus nerve signaling to balance neurotransmitters. These interconnected pathways not only alleviate gastrointestinal discomfort but also provide a solid biological foundation for improving the core behavioral symptoms of ASD, such as social deficits and repetitive behaviors. Future research should focus on establishing standardized exercise intervention protocols, validating the efficacy of these key biological pathways using multi-omics approaches, and exploring combined intervention strategies. The results of corollary studies will provide a more robust scientific basis for precision rehabilitation of children with ASD.

【**Keywords**】 Motor activity; Autistic disorder; Gast rointestinal tract; Bacteria; Child

孤独症谱系障碍(autism spectrum disorder, ASD)是一类以社交互动缺陷、沟通障碍及重复刻板行为为主要特征的神经发育性疾病[1-2],患病负担持续凸显[3-5],且常并存胃肠道症状、饮食选择性与体力活动不足[6]。以上因素与肠道菌群改变共同作用于核心症状与共病[7]。

近年来,肠道菌群(gut microbiota, GM)在 ASD 中的作用日益受到重视。GM 由多种微生物构成,参与营养吸收、能量代谢与免疫调节[8-9];研究显示,ASD 患儿 GM 的组成及多样性与健康儿童存在明显差异,如厚壁菌门和拟杆菌门的比例失衡,以及梭菌属、阿克曼氏菌等菌属丰度异常[10-11]。肠道菌群可通过“肠脑轴”与神经系统形成双向通讯,影响神经递质释放、免疫反应及脑功能[12-14]。菌群紊乱导致的代谢产物变化及炎症反应,可能加重 ASD 的临床症状[15-16]。已有研究发现,运动能够改善肠道微生态环境,提升 GM 多样性,促进有益菌群的增殖,并可能通过修复肠屏障、调节代谢及神经递质通路,间接改善 ASD 症状[17]。本文以运动对 ASD 儿童肠道菌群影响的“机制—研究进展—临床”为主线,为 ASD 综合干预提供理论参考和科学依据。

1 ASD 儿童 GM 失调的核心特征

ASD 儿童的 GM 组成和多样性与正常儿童相比

【基金项目】 科技部“十四五”国家重点研发计划项目(2022YFC3600204)

【作者简介】 潘祥(1998-),男,山东临沂人,在读博士,主要研究方向为身体活动促进与儿童青少年运动干预机制。

【通信作者】 张彦峰,E-mail: zhangyanfeng0310@126.com

存在差异[9]，表现为 α 多样性降低，且 β 多样性变化显著，表明其菌群整体结构与健康对照组有显著差别[18]。在具体菌种层面，众多研究显示 ASD 儿童厚壁菌门丰度增加、拟杆菌门丰度减少，导致厚壁菌与拟杆菌的比例上升[19-20]。具体变化还包括梭菌属的丰度增加，与 ASD 的胃肠道症状及异常行为可能相关[21]，特别是潜在致病性强的艰难梭菌（*C. difficile*）[22]，关于阿克曼氏菌的变化则呈争议状态，研究结果各不相同[9]，而公认的具有肠道保护作用的双歧杆菌属在 ASD 患者中的丰度普遍降低[23-24]。除厚壁菌门与拟杆菌比值上升与双歧杆菌属下降外，产丁酸菌（普拉梭杆菌等）与普雷沃氏菌普遍减少[25-27]，并伴随代谢产物谱异常［如短链脂肪酸（short-chain fatty acids，SCFAs）改变］[28]，共同指向能量代谢与屏障稳态受损。

以上菌群组成的改变并非偶然，大型前瞻性出生队列研究已经证实，在婴儿期观察到的肠道微生物特征，可以作为预测未来儿童神经发育障碍的重要生物标志物[29]。在后来被诊断为 ASD 的婴幼儿肠道中，通常会观察到有益菌可能富集[29]。早期的菌群失调模式支持了 ASD 病理生理学的“生命早期起源”假说，即早期免疫失调、代谢紊乱与遗传风险因素相互作用，共同影响了神经发育轨迹[30]。

2 运动调节 GM 的研究进展

近年来的研究显示，运动能够显著改善健康人群的肠道微生态，主要体现在菌群多样性和特定益生菌丰度的增加，以及肠道屏障与免疫功能的改善上[17]。多项临床与动物研究都指出，运动能够显著提升 GM 的 α 多样性（群落内物种的丰富度与均匀度）。如有极高身体活动的儿童肠道菌群结构与久坐儿童相比表现出更高的多样性和有益菌丰度[31]，动物模型同样证实运动干预可提高小鼠的 GM 多样性[32]，并调节厚壁菌门与拟杆菌门的比例[33]。但该效应受饮食与能量摄入的影响，且不同测序、统计流程可能导致 α 和 β 多样性方向不一致[17,34-35]。运动诱导肠道微生态的有益变化，还表现为特定益生菌的增殖，包括产生 SCFAs 的菌种，如阿克曼氏菌和普拉梭杆菌等[36]。

同时，运动能够显著改善 ASD 儿童的核心症状及相关共病问题[37-38]。对于 ASD 核心症状的改善，首要体现在重复行为的缓解。研究表明，为期 12 周的游泳干预运动降低了 ASD 儿童的重复刻板行为频率与强度[39]。最新荟萃分析也指出，运动对 ASD 核心症状与睡眠、焦虑呈小至中等效应量；团队、双人项目在社交分量表上效应更稳[40-41]。在共存症状方面，运动同样表现出良好的改善效果。运动可以促进多种神经递质的释放，不仅能有效缓解焦虑与抑郁情绪，还能帮助 ASD 儿童建立更为稳定的睡眠节律，从而改善睡眠质量，减少入睡困难及夜间觉醒等问题[42]。

产生 SCFAs 的菌种增加可促使 SCFAs（如乙酸、丙酸和丁酸）的生成，从而提供能量、抑制炎症反应、增强肠道屏障的完整性，并提升局部及全身免疫功能[17]。而长期锻炼在部分研究中与厚壁菌门某些有益类群和疣微菌门（如阿克曼氏菌）相对丰度上升相关，但不同研究结果存在异质性，受饮食与体能水平显著影响[43]。在动物模型及部分临床研究表明，长期规律的运动能够提高肠道黏膜中紧密连接蛋白的水平，降低肠道通透性与炎症反应[44]，并通过增强肠道分泌型免疫球蛋白 A 等局部免疫机制强化肠道黏膜的防御能力[17]。但从现有证据来看，不同类型（如有氧运动、抗阻训练、高强度间歇训练等）的运动在对 GM 的具体作用与机制方面尚需进一步深入研究。

3 运动调控 GM 改善儿童 ASD 症状的生物学机制

运动对 ASD 儿童肠道菌群的调控并非单一作用，而是通过多条相互关联的生物学通路实现的。为系统性地阐述这些机制，研究从肠道屏障-炎症轴、代谢产物-肠脑对话轴以及神经递质前体-代谢轴 3 个核心层面进行深入论述。

3.1 运动通过修复肠道屏障完整性以抑制脂多糖（lipopolysaccharide，LPS）介导的神经炎症

肠道菌群紊乱可损伤肠道黏膜通透性，驱动炎症因子及 LPS 经肠道进入血液循环，诱发低度全身炎症反应，部分炎性因子能够透过血脑屏障引起神经炎症，从而进一步干扰脑功能[13]。由“肠道通透性增加”引发的神经炎症在 ASD 的病理生理学中扮演着核心角色[45]。肠道屏障受损使得通常被限制在肠腔内的细菌成分 LPS 得以进入体循环，激活免疫反应并诱导血液炎症状态[46]。当炎症信号传递到中枢神经系统时，会触发小胶质细胞的异常活化，引起持续的神经炎症，被认为是导致或加剧 ASD 核心行为症状（如社交障碍、重复刻板行为）的重要生物学基础[47]。

中等强度有氧或抗阻训练可上调肠黏膜紧密连接蛋白（zonula occludens-1、Occludin）与分泌型免疫球蛋白 A（secretory immunoglobulin A，sIgA），降低脂多糖结合蛋白（lipopolysaccharide-binding protein，LBP）、C-反应蛋白（C-reactive protein，CRP）等炎症标志物[17,44,48]。运动通过多种途径强化这一防御体系，增加对肠道屏障至关重要的特定菌群丰度[17,44]，如阿克曼氏菌和产丁酸菌。阿克曼氏菌以肠道黏液

为食，能刺激杯状细胞产生更多黏液，从而加固物理屏障；而丁酸盐等 SCFAs 是肠上皮细胞的主要能量来源，能促进紧密连接蛋白的合成，封堵细胞间隙[49]。其次，运动还能提升 sIgA 的水平。sIgA 作为肠道黏膜免疫的关键分子，能有效结合并中和 LPS 及其他病原体，阻止其穿透屏障[17,48]。此外，运动通过增加肠道蠕动，加速食物残渣与代谢废物的排出，从而降低有害菌的定植风险，促进有益菌的繁殖[34,50]，同时还通过调节肠道的局部免疫活性，降低肠黏膜的炎症反应和肠道的通透性，从而直接改善 GM 生长的生态环境[48,51]。

3.2 *运动通过优化关键代谢产物重塑肠脑对话* SCFAs，尤其是丁酸等菌群代谢产物在 ASD 患儿体内水平降低，可能进一步加剧肠道屏障损伤和血脑屏障通透性升高[17]。SCFAs 是肠道菌群发酵膳食纤维产生的核心代谢产物，不仅是能量物质，更是连接肠道与大脑的关键信号分子[29]。运动可富集产丁酸菌（普拉梭杆菌、罗氏菌属等），提升丁酸、丙酸水平，经 G 蛋白偶联受体 41/43 与过氧化物酶体增殖物激活受体 γ 抑制核因子 κB 炎症轴、促进调节性 T 细胞稳态并修复屏障[14,52-53]。

丁酸盐是一种天然的组蛋白去乙酰化酶（histone deacetyfase，HDAC）抑制剂，能够穿过血脑屏障，直接影响中枢神经系统[54]。在大脑内，丁酸盐通过抑制小胶质细胞的过度活化来减轻神经炎症，且可调节基因的表观遗传修饰，影响与突触可塑性、神经元生长和社交行为相关的基因表达，对于改善 ASD 的核心缺陷具有深远意义[54-55]。ASD 常见 SCFAs 下降与产丁酸菌不足[23]，而对甲酚等芳香族代谢物升高与症状严重度相关[56-58]；因此，阐明运动是否能够通过整体性地优化菌群结构来同时降低对甲酚等有害代谢物的水平，是全面验证“炎症—屏障—行为”干预链条的关键环节，也是未来研究的重要方向。

3.3 *运动协同菌群调节神经递质前体代谢与通路* GM 可通过肠脑轴直接影响宿主神经递质的合成及代谢，例如菌群通过调控色氨酸代谢途径影响血清素[5-羟色胺（5-hydroxytryptamine，5-HT）合成[25,52]；某些菌群能够直接或间接产生 γ-氨基丁酸（gama-aminobutyric acid，GABA），影响宿主的情绪与认知功能[17]；GM 的变化亦可能导致多巴胺、谷氨酸与乙酰胆碱等多种重要神经递质的功能异常[1]。

色氨酸是合成神经递质血清素的关键前体，代谢路径受肠道菌群的影响。产芽孢细菌等肠道菌群可调节肠嗜铬细胞功能活性，并通过改变身体前体色氨酸和 5-HT 的代谢来影响大脑的功能状态[59]。在 ASD 等应激状态下，色氨酸代谢会偏向犬尿氨酸（kynurenine，KYN）通路，下游代谢物具有神经毒性，可能损害神经功能[60]。运动诱导骨骼肌过氧化物酶体增殖物激活受体 γ 共激活因子 1α-犬尿氨酸氨基转移酶轴将 KYN 转化为犬尿酸，从而降低外周 KYN 负荷并减少其跨血脑屏障后的潜在神经毒性[61]；肠菌调控色氨酸向 5-HT、吲哚路径分流，影响情绪与感觉处理[26,59]。以上发现共同揭示了运动与菌群在色氨酸代谢调控上的协同潜力：运动通过外周肌肉直接清除潜在的神经毒性代谢物，而健康的菌群则从肠道源头促进有益神经递质的合成，为缓解 ASD 相关的焦虑和注意问题提供有力的生物学解释。

除调节这些化学信号分子外，运动还能影响直接的神经通路，如改变胆汁酸合成与肠肝循环，微生物生成次级胆汁酸经法尼醇 X 受体和 G 蛋白偶联胆汁酸受体 1 重塑代谢与炎症[44]；提升迷走神经张力，抑制炎症反应并改善肠动力[48,62]。鉴于 ASD 常见胃肠动力异常，该通路为运动干预如何强化并改善腹痛、便秘等症状提供了直接的神经机制解释[15]。

综上所述，以上证据共同描绘了运动干预的多维作用机制：不仅通过影响屏障和代谢产物来调节肠脑间的“化学通讯”，也通过干预色氨酸代谢和强化迷走神经通路来优化“神经通讯”，类似机制的协同作用共同构成了改善 ASD 微生态与症状的生物学基础。

4 运动干预的临床实证

4.1 *运动干预 ASD 实证* 动物模型及临床研究表明，运动在调节 ASD 儿童 GM 结构与功能方面具有积极作用[50-51,63]。在母体免疫激活诱导的 ASD 小鼠模型中，早期进行的运动干预可以改善小鼠的社交行为，并增加肠道内有益菌的丰度，减少致病菌的生长[11]。跑步运动同样改变了 ASD 动物模型的肠道微生物及其代谢产物，并缓解了焦虑倾向[50]，GM 在 ASD 小鼠运动干预中发挥了积极且关键的调节作用[64]也进一步证实了这一点。

针对 ASD 儿童的运动干预研究显示，在有监督的运动后，儿童的 GM 丰度显著提升，同时粪便中的 SCFAs 浓度也有所增加，相关的胃肠道症状明显减少，ASD 相关行为改善[51]。另有干预研究观察到普拉梭杆菌等产丁酸益生菌丰度增加，伴随受试儿童在社会沟通上的表现改进[64]。尽管结果积极[63]，但目前的临床研究普遍存在样本量小、缺乏严格的对照组、干预手段多样、长期随访不足及微生物群测序技术精度有待提高等局限性[35]。

4.2 *联合干预的协同作用* 近年来研究发现，特定饮

食模式可能改善 ASD 儿童肠道菌群，与运动的协同逻辑包括高纤维、益生元为 SCFAs 提供底物放大运动效应；益生菌可缩短微生态重建时间窗；粪菌移植后运动有助屏障恢复与定植维持[34,65-66]。尽管关于“运动+饮食、益生菌、粪菌移植”的临床证据有限，但从机制上存在明确的叠加逻辑：运动通过改善肠动力、降低低度炎症并修复屏障，为有益菌的生长奠定有利的生态基础[17,34,44]；在此基础上，高纤维、益生元饮食则提供充足的发酵底物，从而放大 SCFAs 的运动产出效应[34,65]；在通过益生菌与粪菌移植补充外源性有益菌群后，运动的持续作用又能帮助其在已被优化的环境中巩固定植与功能[17,66]。

5 小结与展望

ASD 儿童肠道菌群多样性降低及其相关共病症状日益成为研究热点，肠脑轴机制为干预提供了新的理论框架。运动作为一种安全、低成本且易实施的非药物干预手段，初步研究已证实其在改善 ASD 儿童肠道菌群多样性、调节菌群结构与代谢功能，以及减轻 ASD 核心症状与共病问题方面均表现出较好前景。然而，当前相关研究多为初步探索阶段，仍存在研究样本偏少、运动干预方式及周期设计存在异质性、微生态评估技术尚不统一等问题。

未来研究应注重以下方面：(1)进一步明确不同强度和模式的运动干预对 ASD 儿童肠道菌群及临床症状的具体影响，建立规范化的干预方案；(2)扩大研究的样本量，聚焦长期随访干预效果，明确菌群多样性改善的持续性；(3)探索运动结合其他综合干预措施(如益生菌、益生元及特殊饮食)对 ASD 儿童临床表现及肠道菌群多样性的协同效应。同时，在深入解析运动干预与肠道菌群、肠脑轴的作用机制基础上，未来应发展针对 ASD 儿童更个性化的运动处方，并逐步建立标准化的实施流程与监测评价体系，为提高 ASD 群体的生活质量及远期预后提供重要的医学理论及实践依据。

利益冲突声明 所有作者声明无利益冲突。

参考文献

[1] HE Y, WANG K, SU N, et al. Microbiota-gut-brain axis in health and neurological disease: interactions between gut microbiota and the nervous system[J]. J Cell Mol Med, 2024, 28(18): e70099.

[2] LORD C, BRUGHA T S, CHARMAN T, et al. Autism spectrum disorder[J]. Nat Rev Dis Prim, 2020, 6: 5.

[3] MAENNER M J, SHAW K A, BAIO J, et al. Prevalence of autism spectrum disorder among children aged 8 years - autism and developmental disabilities monitoring network, 11 sites, United States, 2016 [J]. MMWR Surv Summ, 2020, 69(4): 1-12.

[4] WANG F, LU L, WANG S B, et al. The prevalence of autism spectrum disorders in China: a comprehensive Meta-analysis[J]. Int J Biol Sci, 2018, 14(7): 717-725.

[5] CHIAROTTI F, VENEROSI A. Epidemiology of autism spectrum disorders: a review of worldwide prevalence estimates since 2014[J]. Brain Sci, 2020, 10(5): 274.

[6] SHARP W G, BERRY R C, MCCRACKEN C, et al. Feeding problems and nutrient intake in children with autism spectrum disorders: a Meta-analysis and comprehensive review of the literature[J]. J Autism Dev Disord, 2013, 43(9): 2159-2173.

[7] PAGE S D, SOUDERS M C, KRAL T V E, et al. Correlates of feeding difficulties among children with autism spectrum disorder: a systematic review[J]. J Autism Dev Disord, 2022, 52(1): 255-274.

[8] FUNG T C, OLSON C A, HSIAO E Y. Interactions between the microbiota, immune and nervous systems in health and disease[J]. Nat Neurosci, 2017, 20(2): 145-155.

[9] CHARITOS I A, INCHINGOLO A M, FERRANTE L, et al. The gut microbiota's role in neurological, psychiatric, and neurodevelopmental disorders[J]. Nutrients, 2024, 16(24): 4404.

[10] LIU F, LI J, WU F, et al. Altered composition and function of intestinal microbiota in autism spectrum disorders: a systematic review[J]. Transl Psychiatry, 2019, 9(1): 43.

[11] VUONG H E, HSIAO E Y. Emerging roles for the gut microbiome in autism spectrum disorder[J]. Biol Psychiatry, 2017, 81(5): 411-423.

[12] YASSIN L K, NAKHAL M M, ALDEREI A, et al. Exploring the microbiota-gut-brain axis: impact on brain structure and function[J]. Front Neuroanat, 2025, 19: 1504065.

[13] CRYAN J F, O'RIORDAN K J, COWAN C S M, et al. The microbiota-gut-brain axis[J]. Physiol Rev, 2019, 99(4): 1877-2013.

[14] DALILE B, VAN OUDENHOVE L, VERVLIET B, et al. The role of short-chain fatty acids in microbiota-gut-brain communication[J]. Nat Rev Gastroenterol Hepatol, 2019, 16(8): 461-478.

[15] HUGHES H K, ROSE D, ASHWOOD P. The gut microbiota and dysbiosis in autism spectrum disorders[J]. Curr Neurol Neurosci Rep, 2018, 18(11): 81.

[16] SETTANNI C R, IANIRO G, BIBBÒ S, et al. Gut microbiota alteration and modulation in psychiatric disorders: current evidence on fecal microbiota transplantation[J]. Prog Neuropsychopharmacol Biol Psychiatry, 2021, 109: 110258.

[17] MAILING L J, ALLEN J M, BUFORD T W, et al. Exercise and the gut microbiome: a review of the evidence, potential mechanisms, and implications for human health[J]. Exerc Sport Sci Rev, 2019, 47(2): 75-85.

[18] XIE X, LI L, WU X, et al. Alteration of the fecal microbiota in Chinese children with autism spectrum disorder[J]. Autism Res, 2022, 15(6): 996-1007.

[19] MARTÍNEZ-GONZÁLEZ A E, ANDREO-MARTÍNEZ P. Prebiotics, probiotics and fecal microbiota transplantation in autism: a systematic review[J]. Rev Psiquiatr Salud Ment, 2020, 13(3): 150-164.

[20] STRATI F, CAVALIERI D, ALBANESE D, et al. New evidences on the altered gut microbiota in autism spectrum disorders[J]. Microbiome, 2017, 5(1): 24.

[21] FERGUSON B J, MARLER S, ALTSTEIN L L, et al. Psychophysiological associations with gastrointestinal symptomatology in autism spec-

trum disorder[J]. Autism Res, 2017, 10(2): 276-288.

[22] TOMASZEK N, URBANIAK A D, BAŁDYGA D, et al. Unraveling the connections: eating issues, microbiome, and gastrointestinal symptoms in autism spectrum disorder[J]. Nutrients, 2025, 17(3): 486.

[23] XU M, XU X, LI J, et al. Association between gut microbiota and autism spectrum disorder: a systematic review and Meta-analysis[J]. Front Psychiatry, 2019, 10: 473.

[24] RISTORI M V, QUAGLIARIELLO A, REDDEL S, et al. Autism, gastrointestinal symptoms and modulation of gut microbiota by nutritional interventions[J]. Nutrients, 2019, 11(11): 2812.

[25] BERDING K, DONOVAN S M. Microbiome and nutrition in autism spectrum disorder: current knowledge and research needs[J]. Nutr Rev, 2016, 74(12): 723-736.

[26] O'MAHONY S M, CLARKE G, BORRE Y E, et al. Serotonin, tryptophan metabolism and the brain-gut-microbiome axis[J]. Behav Brain Res, 2015, 277: 32-48.

[27] BUNDGAARD-NIELSEN C, KNUDSEN J, LEUTSCHER P D C, et al. Gut microbiota profiles of autism spectrum disorder and attention deficit/hyperactivity disorder: a systematic literature review[J]. Gut Microbes, 2020, 11(5): 1172-1187.

[28] SUN M F, SHEN Y Q. Dysbiosis of gut microbiota and microbial metabolites in Parkinson's Disease[J]. Ag Res Rev, 2018, 45: 53-61.

[29] AHRENS A P, HYÖTYLÄINEN T, PETRONE J R, et al. Infant microbes and metabolites point to childhood neurodevelopmental disorders[J]. Cell, 2024, 187(8): 1853-1873.

[30] SHARON G, CRUZ N J, KANG D W, et al. Human gut microbiota from autism spectrum disorder promote behavioral symptoms in mice[J]. Cell, 2019, 177(6): 1600-1618.

[31] PAN X, GAO Y, ZHANG Y, et al. Gut microbiota differences in children classified by extreme physical fitness and physical activity levels from a Chinese cross-sectional study[J]. Sci Rep, 2025, 15(1): 21351.

[32] MOTIANI K K, COLLADO M C, ESKELINEN J J, et al. Exercise training modulates gut microbiota profile and improves endotoxemia[J]. Med Sci Sports Exerc, 2020, 52(1): 94-104.

[33] IMDAD S, SO B, JANG J, et al. Temporal variations in the gut microbial diversity in response to high-fat diet and exercise[J]. Sci Rep, 2024, 14(1): 3282.

[34] CAMPANIELLO D, CORBO M R, SINIGAGLIA M, et al. How diet and physical activity modulate gut microbiota: evidence, and perspectives[J]. Nutrients, 2022, 14(12): 2456.

[35] FOUQUIER J, MORENO H N, DONNELLY J, et al. The gut microbiome in autism: study-site effects and longitudinal analysis of behavior change[J]. mSystems, 2021, 6(2): e00848.

[36] AYA V, JIMENEZ P, MUÑOZ E, et al. Effects of exercise and physical activity on gut microbiota composition and function in older adults: a systematic review[J]. BMC Geriatr, 2023, 23(1): 364.

[37] YANO N, HOSOKAWA K. The importance of comprehensive support based on the three pillars of exercise, nutrition, and sleep for improving core symptoms of autism spectrum disorders[J]. Front Psychiatry, 2023, 14: 1119142.

[38] FERREIRA J P, GHIARONE T, JUNIOR C R C, et al. Effects of physical exercise on the stereotyped behavior of children with autism spectrum disorders[J]. Medicina, 2019, 55(10): 685.

[39] PAN C Y. Effects of water exercise swimming program on aquatic skills and social behaviors in children with autism spectrum disorders[J]. Autism, 2010, 14(1): 9-28.

[40] WU Y, DING L, ZHANG Q, et al. The effect of physical exercise therapy on autism spectrum disorder: a systematic review and Meta-analysis[J]. Psychiatry Res, 2024, 339: 116074.

[41] TOSCANO C V A, FERREIRA J P, QUINAUD R T, et al. Exercise improves the social and behavioral skills of children and adolescent with autism spectrum disorders[J]. Front Psychiatry, 2022, 13: 1027799.

[42] BRAND S, JOSSEN S, HOLSBOER-TRACHSLER E, et al. Impact of aerobic exercise on sleep and motor skills in children with autism spectrum disorders: a pilot study[J]. Neuropsychiatr Dis Treat, 2015, 11: 1911-1920.

[43] SOLOUKI S, GORGANI-FIRUZJAEE S, JAFARY H, et al. Efficacy of high-intensity interval and continuous endurance trainings on cecal microbiota metabolites and inflammatory factors in diabetic rats induced by high-fat diet[J]. PLoS One, 2024, 19(4): e0301532.

[44] HAWLEY J A, FORSTER S C, GILES E M. Exercise, the gut microbiome and gastrointestinal diseases: therapeutic impact and molecular mechanisms[J]. Gastroenterology, 2025, 169(1): 48-62.

[45] COURY D L, ASHWOOD P, FASANO A, et al. Gastrointestinal conditions in children with autism spectrum disorder: developing a research agenda[J]. Pediatrics, 2012, 130(Suppl 2): S160-S168.

[46] VIGGIANO D, IANIRO G, VANELLA G, et al. Gut barrier in health and disease: focus on childhood[J]. Eur Rev Med Pharmacol Sci, 2015, 19(6): 1077-1085.

[47] DAVOLI-FERREIRA M, THOMSON C A, MCCOY K D. Microbiota and microglia interactions in ASD[J]. Front Immunol, 2021, 12: 676255.

[48] VARGHESE S, RAO S, KHATTAK A, et al. Physical exercise and the gut microbiome: a bidirectional relationship influencing health and performance[J]. Nutrients, 2024, 16(21): 3663.

[49] CHANG P V, HAO L, OFFERMANNS S, et al. The microbial metabolite butyrate regulates intestinal macrophage function via histone deacetylase inhibition[J]. Proc Natl Acad Sci USA, 2014, 111(6): 2247-2252.

[50] XUE Y, AN S, QIU W, et al. Exercise changes gut microbiota: a new idea to explain that exercise improves autism[J]. Int J Sports Med, 2023, 44(7): 473-483.

[51] RANIERI A, MENNITTI C, FALCONE N, et al. Positive effects of physical activity in autism spectrum disorder: how influences behavior, metabolic disorder and gut microbiota[J]. Front Psychiatry, 2023, 14: 1238797.

[52] ALLEN J M, MAILING L J, NIEMIRO G M, et al. Exercise alters gut microbiota composition and function in lean and obese humans[J]. Med Sci Sports Exerc, 2018, 50(4): 747-757.

[53] ARAGÓN-VELA J, SOLIS-URRA P, RUIZ-OJEDA F J, et al. Impact of exercise on gut microbiota in obesity[J]. Nutrients, 2021, 13(11): 3999.

[54] LIAO X, LIU Y, FU X, et al. Postmortem studies of neuroinflammation in autism spectrum disorder: a systematic review[J]. Mol Neurobiol, 2020, 57(8): 3424-3438.

(下转第 1824 页)

gram: quantitative analysis and classification of non-suicidal self-injury [C]//Institute of Electrical and Electronics Engineers Proceedings of 2019 IEEE First International Conference on Cognitive Machine Intelligence (CogMI). Los Angeles, CA, 2019: 61-70.

[35] GOYAL S, DUTTA R, DEV S, et al. MindLift: AI-powered mental health assessment for students [J]. Neurosci Inform, 2025, 5(2): 100208.

[36] WU S, XUE Y, HANG Y, et al. Non-suicidal self-injury prediction with pain-processing neural circuits using interpretable graph neural network [J]. Ann Med, 2025, 57(1): 2520394.

[37] LIANG Z, YE W, LIU Q, et al. NSSI-net: a multi-concept GAN for non-suicidal self-injury detection using high-dimensional EEG in a semi-supervised framework [J]. IEEE J Biomed Health Inform, 2025, 29(8): 5452-5464.

[38] CHEN W, YI Z, LIM L J R, et al. Deep learning and remote photoplethysmography powered advancements in contactless physiological measurement [J]. Front Bioeng Biotechnol, 2024, 12: 1420100.

[39] ALAMGIR F M, ALAM M S. An artificial intelligence driven facial emotion recognition system using hybrid deep belief rain optimization [J]. Multimed Tools Appl, 2023, 82(2): 2437-2464.

[40] ZHU Y, REN W, YANG L, et al. Relationship between facial emotion recognition and non-suicidal self-injury in adolescents with depression: a multicenter cross-sectional study from China [J]. J Affect Disord, 2025, 383: 394-400.

[41] ZHEN Y, LIU P, JIANG L, et al. EEG signatures and effects of mindfulness approaches in adolescents with nonsuicidal self-injury [J]. Psychophysiology, 2025, 62(6): e70085.

[42] SILK J S, PRAMANA G, SEQUEIRA S L, et al. Using a smartphone app and clinician portal to enhance brief cognitive behavioral therapy for childhood anxiety disorders [J]. Behav Ther, 2020, 51(1): 69-84.

[43] DESHPANDE S, WARREN J. Self-harm detection for mental health chatbots [J]. Stud Health Technol Inform, 2021, 281: 48-52.

[44] RODANTE D E, CHIAPELLA L C, OLIVERA FEDI R, et al. A randomized 3-month, parallel-group, controlled trial of CALMA m-health app as an adjunct to therapy to reduce suicidal and non-suicidal self-injurious behaviors in adolescents: study protocol [J]. Front Psychiatry, 2023, 14: 1087097.

[45] INKSTER B, SARDA S, SUBRAMANIAN V. An empathy-driven, conversational artificial intelligence agent (wysa) for digital mental well-being: real-world data evaluation mixed-methods study [J]. JMIR Mhealth Uhealth, 2018, 6(11): e12106.

[46] FITZPATRICK K K, DARCY A, VIERHILE M. Delivering cognitive behavior therapy to young adults with symptoms of depression and anxiety using a fully automated conversational agent (woebot): a randomized controlled trial [J]. JMIR Ment Health, 2017, 4(2): e19.

[47] MITTAL S, THAKRAL K, SINGH R, et al. On responsible machine learning datasets emphasizing fairness, privacy and regulatory norms with examples in biometrics and healthcare [J]. Nat Mach Intell, 2024, 6(8): 936-949.

[48] 国家互联网信息办公室. 儿童个人信息网络保护规定: 网信办令第 4 号 [EB/OL]. (2019-08-22) [2025-11-19]. https://www.gov.cn/zhengce/zhengceku/2019-08/22/content_5458118.htm.

[49] HOFWEBER T, WALKER R L. Machine learning in health care: ethical considerations tied to privacy, interpretability, and bias [J]. N C Med J, 2024, 85(4): 240-245.

收稿日期: 2025-08-11 修回日期: 2025-10-11 本文编辑: 汤建军

(上接第 1819 页)

[55] HUANG H, LIU J Q, YU Y, et al. Regulation of TWIK-related potassium channel-1 (Trek1) restitutes intestinal epithelial barrier function [J]. Cell Mol Immunol, 2016, 13(1): 110-118.

[56] ALTIERI L, NERI C, SACCO R, et al. Urinary p-cresol is elevated in small children with severe autism spectrum disorder [J]. Biomarkers, 2011, 16(3): 252-260.

[57] PERALTA-MARZAL L N, PRINCE N, BAJIC D, et al. The impact of gut microbiota-derived metabolites in autism spectrum disorders [J]. Int J Mol Sci, 2021, 22(18): 10052.

[58] TIMPERIO A M, GEVI F, CUCINOTTA F, et al. Urinary untargeted metabolic profile differentiates children with autism from their unaffected siblings [J]. Metabolites, 2022, 12(9): 797.

[59] YANO J M, YU K, DONALDSON G P, et al. Indigenous bacteria from the gut microbiota regulate host serotonin biosynthesis [J]. Cell, 2015, 161(2): 264-276.

[60] ROTHHAMMER V, MASCANFRONI I D, BUNSE L, et al. Type I interferons and microbial metabolites of tryptophan modulate astrocyte activity and central nervous system inflammation via the aryl hydrocarbon receptor [J]. Nat Med, 2016, 22(6): 586-597.

[61] AGUDELO L Z, FEMENÍA T, ORHAN F, et al. Skeletal muscle PGC-1α1 modulates kynurenine metabolism and mediates resilience to stress-induced depression [J]. Cell, 2014, 159(1): 33-45.

[62] CARABOTTI M, SCIROCCO A, MASELLI M A, et al. The gut-brain axis: interactions between enteric microbiota, central and enteric nervous systems [J]. Ann Gastroenterol, 2015, 28(2): 203-209.

[63] MYHRSTAD M C W, RUUD E, GAUNDAL L, et al. Gut microbiota, physical activity and/or metabolic markers in healthy individuals-towards new biomarkers of health [J]. Front Nutr, 2024, 11: 1438876.

[64] SGRITTA M, DOOLING S W, BUFFINGTON S A, et al. Mechanisms underlying microbial-mediated changes in social behavior in mouse models of autism spectrum disorder [J]. Neuron, 2019, 101(2): 246-259.

[65] SONG W, ZHANG M, TENG L, et al. Prebiotics and probiotics for autism spectrum disorder: a systematic review and Meta-analysis of controlled clinical trials [J]. J Med Microbiol, 2022, 71(4): 1-9.

[66] KANG D W, ADAMS J B, GREGORY A C, et al. Microbiota transfer therapy alters gut ecosystem and improves gastrointestinal and autism symptoms: an open-label study [J]. Microbiome, 2017, 5(1): 10.

收稿日期: 2025-07-11 修回日期: 2025-10-19 本文编辑: 王苗苗