

• 综述 •

发育性协调障碍儿童青少年运动干预的研究进展

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摘要: 本文旨在探讨运动干预对发育性协调障碍(DCD)儿童的影响及其生理机制,同时系统回顾了近年来关于运动干预对 DCD 儿童影响的实验性研究。研究表明,运动干预能显著改善 DCD 儿童的运动协调能力,且干预形式呈多样化趋势,从基础运动训练到专项运动训练(如跆拳道、乒乓球),以及结合认知任务的创新性训练方式。通过运动干预能诱导突触可塑性、重塑神经环路、增加灰质体积、调节神经递质系统等途径,促进大脑生理变化,进而提高运动控制能力。这些改变通过多条信号通路的激活实现,最终优化了运动相关脑区的功能连接。

关键词: 发育性协调障碍; 运动干预; 神经可塑性; 运动控制; 突触重塑

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Research progress on the exercise intervention for children and adolescents with developmental coordination disorder

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Abstract: This paper aims to explore the effects of exercise interventions on children with developmental coordination disorder (DCD) and their underlying physiological mechanisms, while systematically reviewing recent experimental studies on the impact of exercise interventions on children with DCD. Research indicates that exercise interventions can significantly improve motor coordination in children with DCD, with intervention methods showing increasing diversity, ranging from fundamental movement training to specialized sports training (such as taekwondo, table tennis), as well as innovative training approaches combining cognitive tasks. Exercise interventions can promote brain physiological changes through inducing synaptic plasticity, restructuring neural circuits, increasing gray matter volume, and regulating neurotransmitter systems, thereby enhancing motor control abilities. These changes are achieved through the activation of multiple signaling pathways, ultimately optimizing functional connectivity in motor-related brain regions.

Keywords: developmental coordination disorder; exercise intervention; neural plasticity; motor control; synaptic remodeling

发育性协调障碍(developmental coordination disorder, DCD)作为一种常见的神经发育障碍,其核心特征表现为儿童运动技能习得与执行水平远低于同龄预期,DCD 对日常活动参与、学业成就都会产生一定程度的影响^[1]。我国学龄儿童 DCD 患病率达 5%~9%,男童患病比例明显高于女童,DCD 儿童典型特征包括动作笨拙、平衡能力缺陷、精细动作控制薄弱等,使其学习和生活都受到较大影响^[2]。DCD 对儿童的影响不仅局限于运动领域,还深入渗透至心理健康与社会适应能力等方面^[3]。临床观察发现,DCD 儿童常见焦虑情绪、抑郁症状,同时在同伴关系中遭受排斥现象,致使自尊水平下降,进而引

发社交回避行为^[4]。此类负面影响还会延续至青少年甚至成年时期,对生活质量与职业发展构成长期威胁。因此早期识别机制与干预方案实施对改善 DCD 儿童尤为重要^[5]。研究证实运动干预能显著提升 DCD 儿童运动技能水平与身体协调性,不仅直接增强运动能力,还通过神经可塑性促进机制、执行功能增强通路对认知功能产生正向影响^[6]。

1 发育性协调障碍定义和诊断

DCD 主要表现为个体在运动技能发展上存在障碍,该障碍现象无法归因于智力发育问题、感官系统缺陷或其他已知疾病^[7]。DCD 评定主要参照《美

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国精神障碍诊断与统计手册》(第 5 版)(Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition, DSM-5)与《国际疾病分类(第十版)》(International Classification of Diseases, 10th Revision, ICD-10)^[8]。DSM-5 中明确界定 DCD 核心表现是个体运动技能发展水平明显低于同龄群体正常标准,此类运动障碍严重干扰日常生活,使患儿在学校活动参与度降低、社交互动质量下降或自理能力显著受损。诊断工作中需排除脑性瘫痪、视听觉功

能障碍等医学或神经系统异常情况。ICD-10 诊断标准则以简明方式强调运动协调问题对患儿日常生活构成实质性干扰,同时要求排除其他潜在病理因素^[9]。

2 发育性协调障碍常用评估工具

DCD 评估工具呈多样化特点,涵盖各年龄阶段与多元评估方式^[10]。各量表具备独特适用年龄范围与评估侧重点。见表 1。

表 1 DCD 常用评估量表
Tab. 1 Commonly used scales for assessing DCD

量表名称	适用年龄(岁)	评估方式	主要评估内容	特点和应用	限制
MABC-2	3~16	实操测试	手工灵巧性、球类技能、静态和动态平衡	国际广泛使用、标准化程度高、信效度好	对低龄儿童评估效果较弱,测试时间较长
DCDQ	5~15	问卷调查	动作控制、精细运动/书写、一般协调性	家长填写、操作简便、适合初筛	依赖家长报告,可能存在主观偏差
BOT	4~21	实操测试	精细运动控制、手工协调、身体协调、力量和敏捷性	有完整版和简短版、评估内容全面、可靠性高	需要较高的操作技能,评估时间较长
TGMD	3~10	实操测试	移动技能、物体控制技能	适合基础运动评估、易于操作、标准化程度高	主要针对运动技能,未涉及认知或情感方面
神经运动成熟度评估	0~6	临床观察	原始反射、姿势反应、神经发育水平	适合早期筛查、需专业人员操作、可预测发展趋势	需要专业人员操作,较难普及
ADL	3~18	观察评估	基本生活自理、工具性日常活动	关注功能性表现、实用性强、反映实际生活能力	观察者主观性较强,可能影响结果的准确性
Little DCDQ	3~4	问卷调查	运动协调能力、日常活动表现	专为低龄儿童设计、早期筛查工具、操作简便	仅适用于非常低龄的儿童,评估内容有限
SFA	5~12	观察评估	学校活动参与、任务支持需求、活动表现	针对学校场景、全面评估学习相关技能、可指导教育安置	主要聚焦学校活动,无法全面评估生活其他方面
VMI	3 岁以上	实操测试	视觉感知、运动协调、视觉-运动整合	评估特定能力、标准化程度高、诊断价值高	不适用于评估社交行为或其他非运动性技能
CAPE	6~21	问卷调查	活动参与度、活动偏好、参与模式	了解活动选择、有助于干预计划制定、关注主观体验	依赖主观自评,可能存在个体差异
汉字书写评估量表	6 岁以上	实操测试	书写速度、准确性、书写工整度	适合中文使用者、评估书写技能、有本土化常模	仅适用于中文书写,无法评估其他语言的书写
ETCH	6~12	实操测试	书写速度、字母/数字书写、空间排布	适合英文书写评估、标准化程度高、可靠性好	仅适用于英文书写,无法评估中文或其他语言的书写

注:儿童动作评估测验-第二版(Movement Assessment Battery for Children - Second Edition, MABC-2);发育性协调障碍问卷(Developmental Coordination Disorder Questionnaire, DCDQ);布鲁因克斯-奥泽茨基运动熟练度测验(Bruininks-Oseretsky Test of Motor Proficiency, BOT-2);粗大运动发展测验(Test of Gross Motor Development, TGMD);日常生活活动能力量表(Activities of Daily Living Scale, ADL);幼儿发育性协调障碍问卷(Little Developmental Coordination Disorder Questionnaire, Little DCDQ);学校功能评估(School Function Assessment, SFA);比瑞-布特尼卡视觉-运动整合发展测验(Beery-Buktenica Developmental Test of Visual-Motor Integration, VMI);儿童参与和愉悦评估(Children's Assessment of Participation and Enjoyment, CAPE);儿童书写评估工具(Evaluation Tool of Children's Handwriting, ETCH)。

3 运动干预在发育性协调障碍儿童中的应用

3.1 DCD 儿童运动特点分析 DCD 儿童运动发展呈现显著特异性,该特征主要体现在粗大运动技能、精细运动能力与感知运动整合等多维度上^[11]。DCD 儿童与典型发展儿童间存在明确发展差异^[12],这种差异不仅表现为运动技能获得时间延迟现象,更体现在动作质量与效率方面的显著缺陷^[13]。DCD 儿童精细运动领域特点为动作不稳定表现,写

字过程中常见手部颤抖现象、笔画不连贯问题、字体大小不一致状况等^[14]。物体操控运动中,接球、投掷等活动表现出明显缺陷,动作准确性与流畅性水平低下^[15]。空间感知与身体意识方面,DCD 儿童同样存在明显不足,对身体空间位置判断能力下降,外界环境变化适应能力受到限制^[16]。

基础运动训练的效果研究:Farhat 等^[17]将受试者分为 3 组,实验训练组包括 14 名 DCD 儿童,对照非训练组包括 13 名 DCD 儿童和 14 名典型发育的

儿童。儿童进行为期 8 周的心肺运动试验干预研究,训练组在步行距离、最大心率方面也有显著改善,并且感知消耗明显降低($P<0.05$)。训练整体延迟了 DCD 儿童达到无氧阈的时间,提高了有氧耐力和运动耐力。在另一项研究中, Maharaj 等^[18]对 64 名 6~12 岁的 DCD 儿童进行了为期 8 周、每周 30min 的大体运动训练,包括投掷、接球和投靶等活动。采用儿童运动评定量表评估发现,干预组的整体评分提高了 6.46%,且在球技和平衡能力方面分别提升了 3.54% 和 4.80%。运动学习方面的研究: Busquets 等^[19]通过旋转视觉运动适应任务研究发现,急性运动能显著促进 DCD 儿童的运动学习和注意力,使其表现接近典型发育儿童水平。此外, Cheng 等^[20]探讨了神经肌肉训练的效果,虽然 3 个月的训练未见显著效果,但在 6 个月随访时发现训练组的姿态能量评分较基线降低了 6.8% ($P=0.004$)。基础运动训练的研究表明,无论是心肺运动、大体运动还是神经肌肉训练,都能显著改善 DCD 儿童的基本运动技能和生理功能。

3.2 专项运动训练和运动技能训练 Ma 等^[21]的研究表明,12 周的适应性跆拳道训练对 DCD 儿童具有多方面的积极影响。研究发现跆拳道组在骨骼发育、运动评估量表总分和眼手协调方面都取得显著进步($P<0.017$),特别是在 3 个月($P=0.009$)和 6 个月($P=0.016$)时,眼手协调能力的改善尤为明显。Tsai^[22]的研究则发现,为期 10 周的乒乓球训练能显著改善 DCD 儿童的认知和运动功能。在平衡能力方面, Jahanbakhsh 等^[23]的研究表明,相比单任务训练,结合平衡和认知任务的双任务训练能更有效地提高 DCD 儿童的静态和动态平衡能力($P<0.001$)。这一发现得到了 Navarro-Patón 等^[24]研究的支持,其对 28 名 4.1~5.9 岁的学龄前儿童进行研究,发现专业体育教育干预能显著提升学龄前 DCD 儿童的手动灵巧度($P<0.001$)、瞄准与捕捉($P<0.002$)和平衡能力($P<0.001$)。Saidmamatov 等^[25]对 27 名 DCD 儿童进行了为期 10 周的研究,结果显示接受运动技能训练的干预组在儿童动作评估测验的总百分位排名上显著提升。同样, Saidmamatov 等^[26]的另一项研究也证实,10 周的运动技能训练能显著提升 DCD 儿童的手动灵巧度、瞄准和捕捉能力以及平衡能力($P<0.001$),且这种改善对不同性别的儿童均有效。无论是单项运动(如跆拳道、乒乓球)还是综合性运动技能训练,都能有效改善 DCD 儿童的运动能力,特别是在眼手协调、平衡能力和手动灵巧度等方面。

3.3 创新干预方式和长期效果评估 Zwicker 等^[27]通过夏令营形式开展干预活动,结合任务特定方法与认知策略应用,使 DCD 儿童功能性运动目标完成度获得提升,同时增强了 DCD 儿童尝试新活动的信心水平。Gholhaki 等^[28]研究则从神经心理学角度证实了运动训练有效性,研究发现训练后 DCD 儿童手灵巧性、瞄准接球能力、平衡性方面亦有明显改善表现。Farhat 等^[29]研究进一步证实了运动干预迁移效应存在性,该项研究结果发现,运动训练不仅改善了 DCD 儿童基本运动技能,还促进了非练习技能发展,包括手动灵巧度、球类技能、平衡能力,以及书写质量与速度提升。长期效果方面, Noordstar 等^[30]追踪研究表明,运动干预积极效果能维持至少 3 个月时间,且儿童运动表现、自我感知运动能力与总体自尊方面改善均得以维持。创新干预研究拓展了传统运动训练模式边界,多层面验证了运动干预的有效性。

4 运动干预对发育性协调障碍儿童影响的生理机制

运动干预对 DCD 儿童症状的改善涉及多层次的神经生理学机制。运动训练通过诱导突触可塑性和神经环路重塑来优化运动控制系统^[31]。持续性运动训练能显著增加 DCD 儿童运动皮层和小脑区域的灰质体积,这种结构性变化与运动技能的提升呈正相关^[32]。此外,运动训练可以通过调节突触后致密物的分子组成来增强突触传递效能^[33]。同时,突触前末梢中 Synapsin I (Synapsin I Protein, Synapsin I)、Synaptophysin (Synaptophysin Protein, Synaptophysin)等囊泡相关蛋白的增加,提高了神经递质的释放概率,强化了突触传递^[34]。这种双向分子改变共同促进了突触可塑性建立过程。特定运动训练能够诱导骨骼肌纤维产生适应性变化^[35]。该变化表现为肌纤维中线粒体数量增加状态、氧化酶活性提升现象,以及肌浆网钙离子调控蛋白表达模式重塑结果^[36]。同时,运动神经元兴奋性特征亦发生变化,包括动作电位阈值调节机制与离子通道密度重组现象^[37]。这些变化协同优化了运动单元募集顺序与发放模式,使力量输出调控呈现更精细化特点。

运动训练还能够激活多条相互关联的信号通路^[38]。脑源性神经营养因子(brain-derived neurotrophic factor, BDNF)通过与 TrkB (tropomyosin-related kinase B)受体结合,激活下游 PI3K/Akt (phosphatidylinositol 3-kinase)和 MAPK (mitogen-activated protein kinase)信号级联,促进突触蛋白的

合成和转运^[39]。胰岛素样生长因子-1 (insulin-like growth factor 1, IGF-1) 则通过调节 mTOR (mammalian target of rapamycin) 信号通路, 参与调控蛋白质合成和细胞骨架重组^[40]。这些营养因子介导的信号级联不仅直接促进突触可塑性, 还能调节神经递质系统的功能。例如, BDNF 可以增强多巴胺能神经元的存活和功能, 提高多巴胺的合成和释放^[41]。多巴胺水平的提升又可以通过 D1 样受体激活 cAMP (cyclic adenosine monophosphate)/PKA (protein kinase A) 信号通路, 进一步维持 BDNF 的高表达, 形成正反馈调节。此外, 运动训练还能调节突触间隙中各类神经调质的平衡^[42]。除多巴胺外, 去甲肾上腺素、五羟色胺等单胺类神经递质水平也显著上升, 这些变化优化了基底节-丘脑-皮层环路的信息处理^[43]。通过功能磁共振成像观察发现, 这些分子和细胞水平的改变最终导致运动相关脑区的激活模式更加协调, 功能连接增强, 与运动技能的改善高度相关^[44]。

5 运动干预在发育性协调障碍治疗中存在的问题及展望

运动干预处于 DCD 治疗核心位置, 目前存在多项待解决问题。现有干预方案多采统一模式, 忽视患者个体差异性, 影响效果稳定。部分方案理论基础不足, 评估标准不一, 干预参数缺乏共识, 质量难以保证。干预持续性与泛化性问题尤为突出, DCD 儿童难以长期保持训练效果或将技能应用于实际生活。

未来干预研究应从个体化精准干预角度出发, 依据患者症状特点制定方案, 建立统一评估标准与明确干预参数。干预过程须注重实用技能培养, 同时整合家庭学校资源, 确保训练成果转化为日常生活能力。这种系统化改进将有效提升 DCD 运动干预整体治疗水平。

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