



DOI:10.14188/j.ajsh.20260044

啮齿类模型脊髓损伤后运动功能评估技术进展及展望

李睿¹, 彭碧文^{2*}, 王蕾蕾^{2,3*}

- (1. 武汉大学 生命科学院, 湖北 武汉 430072;
2. 武汉大学 泰康医学院, 基础医学院, 湖北 武汉 430071;
3. 武汉大学 泰康生命医学中心, 湖北 武汉 430071)

摘要: 脊髓损伤致残率高, 患者常遗留永久性运动功能障碍, 给个人、家庭及社会带来沉重负担。啮齿类动物因成本低、世代短、方法学成熟等优势, 在可行性与科学性方面优于灵长类等大动物模型, 已成为临床前研究的主流选择。然而, 现有用于啮齿类脊髓损伤模型的运动功能评估手段普遍存在主观偏差大、量化精度不足、实验室内重复性差等问题, 严重制约了损伤修复疗效的客观评价。近年来, 视觉姿态重建、同步电生理等技术在啮齿类脊髓损伤模型的功能评价中取得了多项突破性进展, 多模态整合评估体系的构建也展现出弥补单一评估方法固有缺陷的巨大潜力。系统综述了近年来各类评估技术在脊髓损伤研究中的应用进展, 涵盖传统行为学、电生理检测和深度学习姿态追踪等技术特点与局限, 并重点阐释了时序同步、多维互证的多模态评估框架的协同优势与现存瓶颈。多模态整合评估体系的持续完善, 将为脊髓损伤修复研究及临床前标准化疗效判定开辟新途径, 并提供关键方法学支撑。

关键词: 脊髓损伤; 功能评估; 啮齿类动物; 深度学习; 多模态评估

中图分类号: Q331

文献标志码: A

文章编号: 2096-3491(2026)04-0331-12

Advances and prospects in motor functional assessment techniques for spinal cord injury in rodent models

LI Rui¹, PENG Biwen^{2*}, WANG Leilei^{2,3*}

- (1. College of Life Sciences, Wuhan University, Wuhan 430072, Hubei, China;
2. Taikang Medical School, School of Basic Medical Sciences, Wuhan University, Wuhan 430071, Hubei, China;
3. Taikang Center for Life and Medical Sciences, Wuhan University, Wuhan 430071, Hubei, China)

Abstract: Spinal cord injury (SCI) has a high disability rate, often leaving patients with permanent motor dysfunction and imposing a heavy burden on individuals, families, and society. Rodent models, owing to their low cost, short generation time, and well-established methodologies, offer superior feasibility and scientific validity compared to large animal models such as primates, and have become the mainstream choice for preclinical research. However, current motor function assessment tools for rodent SCI models are generally plagued by prominent subjective bias, insufficient quantitative accuracy, and poor inter-laboratory reproducibility, which seriously hamper the objective evaluation of therapeutic efficacy. In recent years, technologies such as visual pose reconstruction and synchronous electrophysiological recording have achieved multiple breakthrough advances in functional assessment of rodent SCI models, and the

收稿日期: 2026-07-18 修回日期: 2026-07-29 接受日期: 2026-08-24

作者简介: 李睿(2005-), 男, 研究方向为生物科学, E-mail: 2023302041101@whu.edu.cn

* 通信作者: 彭碧文(1973-), 女, 博士, 教授, 研究方向为胶质细胞对突触活性的影响及机制, E-mail: pengbiwen@whu.edu.cn; 王蕾蕾(1985-), 女, 博士, 教授, 研究方向为神经元重编程与神经损伤的修复治疗, E-mail: Leilei.wang@whu.edu.cn

基金项目: 国家自然科学基金(32370786)

引用格式: 李睿, 彭碧文, 王蕾蕾. 啮齿类模型脊髓损伤后运动功能评估技术进展及展望[J]. 生物资源, 2026, 48(4): 331-342.

Li R, Peng B W, Wang L L. Advances and prospects in motor functional assessment techniques for spinal cord injury in rodent models [J]. Biotic Resources, 2026, 48(4): 331-342.

construction of multimodal integrated assessment systems has also shown great potential to compensate for the inherent limitations of single-modality evaluation methods. This review systematically summarizes recent progress in the application of various assessment technologies in SCI research, covering the technical characteristics and limitations of traditional behavioral assays, electrophysiological detection, and deep learning-based pose tracking, with a special focus on the synergistic advantages and existing bottlenecks of the temporally synchronized, multi-dimensional cross-validated multimodal assessment framework. The continued refinement of multimodal integrated assessment systems will open new avenues for SCI repair research and standardized preclinical efficacy evaluation, while simultaneously providing critical methodological support.

Key words: spinal cord injury; functional assessment; rodent; deep learning; multimodal evaluation

0 引言

脊髓损伤(spinal cord injury, SCI)是中枢神经系统最严重的创伤性疾病之一^[1]。患者常面临不可逆的运动功能丧失,并需长期应对神经病理性疼痛、痉挛及多系统并发症,给个人、家庭及社会带来沉重负担。然而,成年哺乳动物中枢神经系统固有的神经再生能力十分有限,使得SCI修复至今仍是再生医学领域的棘手难题^[2-7]。在过去十余年间,从干细胞移植、神经营养因子递送到神经调控与智能生物材料,多种前沿治疗策略相继涌现^[8-11],并被广泛应用于基础研究。各种策略的体内修复效果、作用时效与作用机制均需依托规范、统一的临床前功能评估体系完成客观量化判定。然而,当前缺乏适配的标准化评价手段,难以准确区分干预带来的真实神经修复与动物自身行为代偿,无法横向对比不同治疗方案的优劣,也不能为后续临床试验设计提供可靠的前期试验依据。现有主流评估手段普遍存在主观性突出、量化精度不足、跨实验室可重复性差等问题,严重制约损伤修复效果的客观判定,延缓临床转化进程^[12-13]。

灵长类^[14]、犬^[15]、猪^[16]等动物在皮层与脊髓的解剖结构、神经传导通路及免疫炎症反应等方面与人类具有可比性,是评估精细抓握、双足步态及复杂感觉运动整合功能的理想模型。然而,当前全球SCI临床前研究仍以啮齿类动物为主导^[17]。啮齿类动物的优势主要体现在3个方面。第一,成本与周期优势:啮齿类饲养成本低、世代周期短,小鼠8~10周、大鼠10~12周即可达性成熟,便于开展大规模研究^[18]。第二,方法学标准化成熟:现有SCI评估工具多以啮齿类为标定对象,跨实验室结果一致性较好^[19]。第三,遗传编辑工具完备:小鼠拥有成熟的转基因、谱系示踪、光遗传和化学遗传学体系,可在统一遗传背景下精准解析特定分子或神经环路^[20]。相比之下,灵长类、犬、猪等大动物SCI模型面临饲养成本高昂、世代间隔长、可用样本量有限、运动评估

量表尚未统一以及存在潜在的伦理问题等制约因素^[21]。但需指出的是,啮齿类优势负重肢体为后肢,不具备灵长类特有的精细手指操作与双足步态模式,因此其评估结果向临床的转化仍需借助非人灵长类等大动物模型或人源化模型进一步验证^[21-23]。

针对上述问题,本文聚焦啮齿类动物SCI运动功能评估方法的方法学演进,系统综述经典行为学检测、电生理记录、以关节追踪为核心的前沿视觉量化技术的进展、应用价值与局限,并讨论多模态整合的可行路径、协同增益与未来发展目标,以期为SCI评估方法的选择、优化与临床转化提供参考(图1)。

1 经典行为学方法

1.1 开放场地观察评分

开放场地评分是脊髓损伤行为学评估的基础手段。1995年,研究者针对大鼠脊髓损伤模型建立BBB评分(basso beattie bresnahan locomotor rating scale),通过分级方式评价后肢运动功能^[24-25];2006年又推出适配小鼠的BMS评分(basso mouse scale),以分级标准完成后肢运动能力评定^[26-28]。两类量表均由实验人员在开放场地环境下人工观测动物后肢关节活动幅度、步态协调性与躯干控制状态,为后续各类行为量化方案提供参考依据。

网格行走试验也是一类常用开放场地评估手段,实验动物在水平网格平台行进,通过统计四肢踏空失误次数、计算失误率来表征肢体运动协调能力,全程依靠人工完成计数采集。该类评估优势在于操作简便、无特殊设备依赖,可整体反映动物运动功能恢复情况^[29-30]。

步态指数(gait index, GI)与Louisville游泳评分(louisville swim scale)分别用于整体步态偏离度评估与小鼠游泳状态下运动功能评定,两类评价手段尤其适用于常规分级量表无法分辨的细微运动功能恢复差异^[31-33]。

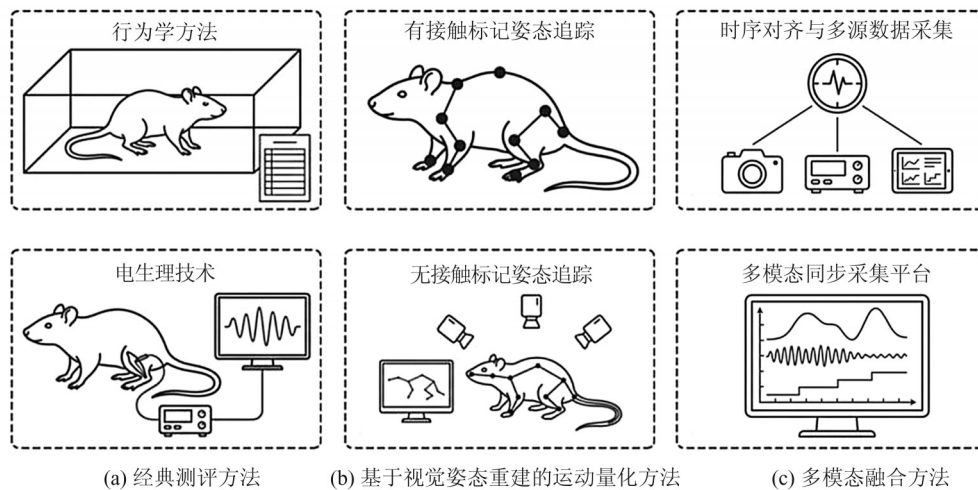


图1 现有啮齿类脊髓损伤运动功能评估方法学框架示意图

Figure 1 Existing methodological framework for motor function assessment in rodent spinal cord injury

注:(a)经典测评方法包含行为学方法与电生理技术;(b)基于视觉姿态重建的运动量化方法包含有接触标记姿态追踪与无接触标记姿态追踪;(c)多模态融合方法借助多模态同步采集平台,支持行为视频、电生理信号、姿态数据等多类信号同步采集,并通过统一时钟实现时序对齐与多源数据采集。

Note: (a) Classic evaluation methods include behavioral methods and electrophysiological techniques; (b) motion quantification methods based on visual pose reconstruction consist of marker-based pose tracking and marker-free pose tracking; (c) the multimodal fusion method, by using a multimodal synchronous acquisition platform, supports the synchronous acquisition of various types of signals such as behavioral videos, electrophysiological signals, and posture data, and achieves time sequence alignment and multi-source data acquisition through a unified clock.

1.2 步态分析

在SCI行为学评估中,半自动化的步态分析相较于传统人工观察能够更敏感地反映功能恢复差异^[34]。为细化开放场地评分难以捕捉的步态细节,研究者建立了多种步态分析技术。染料足印法为早期步态检测手段,通过在动物脚掌涂抹有色染料,使其行走于纸带留存足迹,依靠人工或半自动方式测算步长、步序相关参数^[35-36]。但该方法存在操作复杂、印迹易出现重叠与模糊失真等缺点。依托计算机视觉的分析方法弥补了这一缺点。以CatWalk为代表的光板系统以透光玻璃跑道搭配内置光源为载体,动物爪掌接触板面产生光散射信号,底部高速相机同步采集爪印面积、受力强度、运动时序,配套软件自动提取步长、步频、支撑时相、肢体对称度等步态参数,适用于动物自主行进状态下的步态记录^[37-38]。除上述方法外,多类自动化与高分辨率步态分析系统已在SCI评估中获得应用:DigiGait借助跑步机底部高速摄像采集动物脚印影像,并自动解析步态时序与节律参数^[39-41];高分辨率视频结合自动化图像处理(如开源工具SLEAP)可低成本获取步长、步频、足迹角度等参数,被用于更细致的肢体间协调与对称性评估,这些方法进一步弥补了脚印模糊与人工量化精度不足的缺陷^[42]。

1.3 前肢精细运动与肌力评估

颈段脊髓损伤模型主要考虑上肢功能损伤,而BMS评分侧重关注后肢瘫痪程度及其恢复情况,无法对前肢损伤程度进行评定。FLAS量表(forelimb locomotor assessment scale)适用于大小鼠颈段脊髓损伤,关注前肢掌面接触、关节活动、伸肌与肩胛活动等关节的运动能力,对前肢运动状态分级打分。FLAS量表是颈段损伤研究中的主流人工评价量表^[43-44]。

前肢握力测试结合食物抓取观测与力传感定量检测,操作简便、数据客观,既能定性观察抓取精细动作,又能量化前肢肌力数值,用于定量评估颈髓损伤后的肌力恢复水平^[44-46]。圆柱筒测试记录动物攀爬时双侧前肢支撑频次并计算不对称指数,依托动物自发行为,应激干扰小,灵敏反映前肢自主使用偏侧化问题^[47]。阶梯与横梯行走测试通过统计前肢踏空失误率,评估动态运动下的肢体空间定位与多关节协同能力,可弥补单纯握力测试仅能检测静态肌力的局限,全面反映前肢精细协同运动能力^[47]。

2 电生理评估

2.1 经典电生理方法

脊髓损伤研究中常规使用的电生理检测手段包含运动诱发电位(motor evoked potential, MEP)与

肌电图(electromyogram, EMG)。MEP通过经颅电刺激大脑运动皮层,于下肢肌肉采集诱发电位,以波幅、潜伏期作为观测参数,用于皮质脊髓束传导通路相关检测。现有研究显示,脊髓损伤后MEP波幅显著下降与皮质脊髓束传导受损密切相关;恢复期MEP波幅回升趋势与BBB评分等行为学改善存在显著时间同步性^[48-49]。皮层内微刺激(intracortical microstimulation, ICMS)通过直接刺激运动皮层并记录相应肌肉或肢体反应,可用于评价皮层运动输出及皮质脊髓通路的功能连接,但该方法具有侵入性。此外,脑干听觉诱发电位(brainstem auditory evoked potential, BAEP)与视觉诱发电位(visual evoked potential, VEP)在合并脑干或视神经损伤的SCI模型中可作为辅助评估手段^[50]。肌电图依托植入式电极或表面电极采集肢体自主运动过程中的肌电信号,以信号强度、频率完成肌肉激活程度量化,既可捕捉损伤后纤颤电位、异常自发放电等神经支配特征,也能同步记录屈伸肌群协同激活、同步共收缩等运动调控模式。肌电图能够区分肉眼难以分辨的细微肌肉激活差异,精准表征脊髓损伤后反射环路重塑、痉挛病理性放电、肌群运动协调紊乱等神经功能表型^[51-52]。

2.2 多通道电生理记录

诱发电位主要评估受损脊髓的信号传导能力,然而该类技术仅能采集外部刺激诱导产生的电位信号,无法测量小鼠清醒状态下自发运动过程中的神经电活动。近年来逐步发展出长期植入式多通道EMG^[51]、脊髓局部场电位慢性记录^[53-54]等技术体系,可在动物自由活动状态下同步采集脊髓环路活动、后肢多肌群肌电信号、痉挛相关病理性放电数据,用于脊髓反射通路重塑、感觉运动耦合等神经电生理机制的数据采集工作。这类技术优势在于无需对动物进行束缚与外源刺激,贴合自然运动状态,可连续长时程采集多位点同步电信号;可量化肌群协同放电、脊髓环路自发振荡、痉挛异常放电等诱发电位无法捕捉的内源神经活动,弥补诱发电位仅能评价下行传导通路的局限。

除了上述技术,高密度皮层脑电图(high-density cortical electroencephalogram, HD-EEG)与皮层脑电图(electrocorticography, ECoG)可在体表或皮层表面记录高频振荡,用于评估皮层-脊髓耦合^[55-57];慢性皮层内微电极阵列^[58-59]可同步记录数百个单细胞放电活动,揭示皮层与脊髓神经元的群体编码特征;神经尘等微型化无线记录技术为自由运动状态下的长期神经活动监测提供了轻量化、无线

缆干扰的新手段^[60];双光子钙成像与电生理同步记录能够在细胞与亚细胞尺度上观测胞内钙信号与电活动的耦合关系,解析神经元活动的分子细胞机制^[61-63]。

3 基于视觉姿态重建的运动量化方法

动物运动行为量化是解析神经功能、评估干预疗效的核心基础,躯体运动精准捕捉长期制约着神经行为学实验的标准化发展与学科进步^[23,64]。然而,由于技术手段等限制,经典评估手段如人工分级、单一足迹参数或肌电峰值等将完整连续运动简化为量表或代表值,仅能反映动物完整连续的全身运动的有限特征。这种简化既会主动舍弃大量躯体姿态信息,又引入人工评判的主观偏差,不仅难以区分神经实质修复与行为代偿,也阻碍不同干预方案的横向对比。随着技术手段的进步,近年来涌现的新方法正逐步填补这一缺陷。

以Vicon系统^[65-66]为代表的有标记光学运动捕捉方案早期以体表粘贴微型反光贴片为标准方案,通过胶水将半球形反光标记固定于动物关节皮毛或皮肤表面,多机位红外相机同步采集反光点信号,重构三维运动轨迹,短时精细运动检测精度优异^[67-68]。但贴片标记易被动物撕咬、脱落,会干扰自然活动,难以开展长时连续行为监测;同时,肢体遮挡场景下还易出现轨迹中断与关键点丢失问题。有部分研究搭配IMU(inertial measurement unit)惯性传感单元形成混合采集方案,依靠惯性数据弥补光学追踪遮挡丢点缺陷^[69]。

以DeepLabCut^[70-72](DLC)为代表的无标记深度学习姿态重建,是基于计算机视觉技术的深度学习神经网络模型的脊髓损伤研究主流工具。其依靠预先训练的神经网络自动识别躯体解剖关键点,输出二维、三维连续坐标。该类算法通用性强:OpenPose^[73]、HRNet^[74]适用于多动物群体与社交行为分析;AlphaTracker^[75]提升小样本、罕见姿态识别效果。全程无需粘贴标记,不干扰动物活动,可长期采集旷场、跑步机、游泳等多范式视频,硬件成本低,是常规实验室自动化量化优选。无标记方案硬件门槛更低,但识别精度易受训练标注数据集、环境光照、肢体相互遮挡等因素限制。

然而,理想中的姿态重建在一些实验条件下仍难以全面实现。动物自然行为均发生在三维空间,单视角二维视频会丢失深度信息,肢体遮挡等问题也无法依靠二维数据消除,仅靠二维追踪难以完整还原复杂运动特征。Anipose结合多视角成像实现

全身三维重建,适配绳梯、转角等复杂行为^[23];同期,SLEAP(social LEAP estimates animal poses)等无标记姿态追踪工具进一步推动了该方向^[76]。理论上,全身数字化姿态重建可保留动物躯体运动细节,并进一步提取步态、关节运动及身体姿态等运动学指标,实现运动信息的客观量化。若进一步与电生理信号同步采集,则可建立运动学与神经电活动之间的时序对应关系。然而完整三维数字化重建需要多相机同步采集与多视角标定,并依赖严格的三角定位与海量时序数据运算^[77],硬件与算力门槛较高,难以在常规实验室普及。因此,关节关键点追踪目前已成为脊髓损伤运动评估中较为常见的自动化视觉量化路径之一。随着计算机技术的快速发展,该方法或许会随之获得进一步突破。

4 多模态评估方法

经典的单一评估方法仅能反映运动恢复的单一层面,易造成疗效误判。此外,多维数据时序不同步,难以建立脊髓结构、神经电活动与运动表型的对应关系;同时,反复束缚与侵入式检测会诱发动物的应激,干扰基线,放大实验误差。因此,同步采集行为、电生理、运动学等多维数据并以统一标准综合判读,是评估方法学的未来发展方向^[78]。多模态整合是一种开放分析框架,所有满足同步采集、统一数据规范的各项指标均可纳入联合评价。

行为学量化、植入式电生理记录、深度学习无标记运动捕捉均已实现全流程数字化连续采集,搭建起多模态同步评估初步技术底座^[65,79]。而同步触发硬件输出统一时钟信号,能够实现毫秒级多源信号对齐,解决数据时序错位问题,支撑跨维度联动分析。

现阶段多模态评估可灵活搭配影像、电生理、运动学等多种检测手段,组合形式丰富多样,而运动学联合电生理是脊髓损伤领域应用的一类典型、成熟的方案。基础研究中,依托DLC开发的MotorBox、MotoRater两套无标记追踪平台可同步实现无标记追踪与BMS行为评分匹配^[80]。整套方案无需粘贴标记、对动物无应激干扰,能够自动量化四肢关节三维轨迹、步态不对称指数与关节畸形活动范围,可检测出传统人工量表无法识别的急性期肢体畸形、慢性步态失衡,实现损伤程度精细化区分。基于大脑皮层、脊髓、外周神经与下肢肌群的多点同步采集系统实现了自由活动大鼠皮层神经元锋电位、脊髓局部场电位、坐骨神经场电位及下肢肌群肌电信号的

同步采集与毫秒级时序匹配;同时,借助同步的高速摄像与二维关节标记点追踪获取后肢运动学参数^[53]。该技术框架为揭示脊髓神经活动与肢体步态周期之间的动态调控关系提供了重要的多模态同步记录手段。临床研究方面,针对不完全脊髓损伤患者开展的多模态检测系统能够同步记录三维步态参数、下肢表面肌电图与ISNCSCI(international standards for neurological classification of spinal cord injury)神经功能评分^[81],依靠多指标交叉验证规避主观评判偏差,能够有效区分代偿性步态与真实神经通路修复,精准量化经皮脊髓刺激、机器人步态训练等康复手段的短期与长期疗效,为制定个体化康复方案提供客观量化支撑^[82]。

现有技术证实多模态联用具备单一检测不具备的协同优势。采用多模态联合分析模型可大幅提升有效干预手段的识别精度,能够捕捉单一指标无法覆盖的损伤与恢复特征;依托多维度数据交叉校验可弥补单一指标的片面性,直观展现行为、电生理等维度观测结果存在的差异与矛盾^[75,83-84]。同步记录多类观测数据还能清晰区分干预产生的即时效应与滞后效应^[85],完成单一检测难以实现的时序动态规律解析;依托同步测量技术可同步采集多类指标,能够在毫秒至数日的多尺度时间范围内,直接关联关节运动模式、肌肉电活动、脊髓组织结构变化与整体运动功能的动态演变过程。

但多模态体系仍存在多项待解决问题:各检测手段固有缺陷无法通过融合消除,深度学习姿态追踪跨实验室重复性不佳。统一数据标准、同步方案与联合统计框架尚未完善,亟须构建标准化啮齿类SCI行为数据库、统一统计口径并推进多中心研究;海量高维数据缺少适配的分析与可视化工具,配套方法学亟待完善^[86-89]。

5 展 望

本文系统梳理了近年来啮齿类脊髓损伤模型运动功能评估方法的发展脉络,依次梳理了经典行为学检测、电生理记录与基于深度学习的视觉姿态追踪三类主流评价技术的操作流程与适用场景,并论述了脊髓损伤临床前运动评估正经历从人工定性分级、单时间截面零散检测,向自动化、客观量化、多模态同步联合判定的范式转型^[12,76]。啮齿类脊髓损伤运动功能评估各方法汇总见表1。本节末尾将从3个方面重点阐述该领域评估体系未来发展展望(图2)。

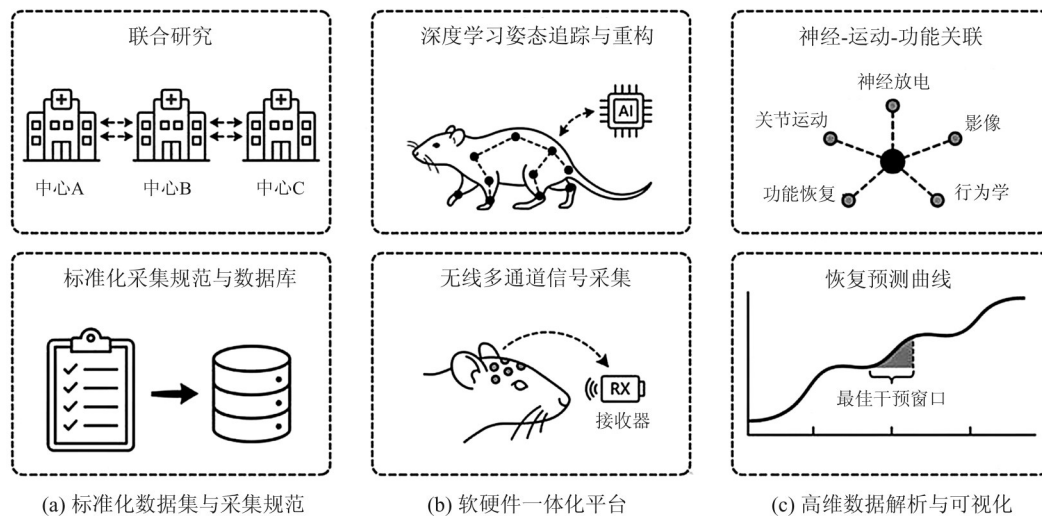


图2 啮齿类动物脊髓损伤运动功能多模态评估体系未来发展框架示意图

Figure 2 Schematic diagram of the future development framework for multimodal motor function evaluation system in rodent spinal cord injury

注:(a)标准化数据集与采集规范建设包含多中心联合探究赋能数据互用与建立标准化采集规范与数据库;(b)软硬件一体化平台建设包含构建AI辅助的深度学习姿态追踪与重构新方案与开发无线多通道信号采集技术;(c)高维数据解析与可视化发展包含神经-运动-功能关联的多维度数据采集与解析和依托多维数据构建恢复曲线并用于最佳干预窗口预测。

Note: (a) The development of standardized datasets and collection norms involves multi-center joint exploration to enable data interoperability and the establishment of standardized collection norms and databases; (b) the construction of an integrated software and hardware platform includes building a new solution for AI-assisted deep learning pose tracking and reconstruction, alongside the advancement of wireless multi-channel signal acquisition technologies; (c) the development of high-dimensional data analysis and visualization involves the acquisition and analysis of multi-dimensional data related to neuro-motor-functional correlation, as well as the construction of recovery curves based on multi-dimensional data for the identification of optimal intervention windows.

表1 啮齿类脊髓损伤运动功能评估方法汇总

Table 1 Overview of motor functional assessment methods in rodent models of spinal cord injury

分类	方法	观测指标	观测结果
行为学检测	BBB 评分 ^[24]	后肢关节活动幅度、步态协调能力与躯干控制能力	0~21分评分
	BMS 评分 ^[26]	小鼠后肢关节活动、步态协调	0~9分评分
	网格行走试验 ^[29]	四肢踏空失误总次数	踏空总次数与肢体踏空失误发生率
	步态指数(GI) ^[31]	整体步态偏离度	连续分值(0~100分)
	Louisville 游泳评分 ^[32]	游泳状态后肢运动功能	0~15分评分
	染料足印法 ^[35]	步长、步序参数	步长、步序、步频、步宽
	CatWalk 步态分析 ^[37]	爪印面积、受力强度、运动时序	步长、步频、摆动相/支撑相比、对称指数
	DigiGait 步态分析 ^[39]	跑步机腹视脚印图像	步态时序与节律参数
	FLAS 量表 ^[43]	前肢掌面接触、关节活动、伸肌/肩胛活动	0~17分评分
	前肢握力测试 ^[45]	抓取动作+力传感信号	肌力绝对值
电生理检测	圆柱筒测试 ^[46]	双侧前肢支撑频次	前肢使用不对称指数
	运动诱发电位(MEP) ^[48]	经颅电刺激+下肢肌肉记录	波幅、潜伏期
	皮层内微刺激(ICMS) ^[50]	皮层内刺激	诱发运动阈值电流
	脑干听觉诱发电位(BAEP) ^[50]	听觉刺激	波幅、潜伏期
	视觉诱发电位(VEP) ^[50]	视觉刺激	波幅、潜伏期

续表

分类	方法	观测指标	观测结果
	肌电图(EMG) ^[51]	表面/植入电极信号	积分肌电值、均方根振幅、中位频率
	脊髓局部场电位(LFP)慢性记录 ^[53]	自由活动状态下脊髓场电位	场电位波形、功率谱密度
	高密度皮层脑电图(HD-EEG) ^[55]	体表皮层高频振荡	高密度头皮电位分布图
	皮层脑电图(ECoG) ^[55]	皮层表面高频振荡	皮层电位分布图
	慢性皮层内微电极阵列 ^[58]	数百单细胞放电活动	单细胞动作电位序列
	神经尘 ^[60]	微型无线神经记录	自由活动长期神经活动数据
	双光子钙成像+电生理同步 ^[61]	细胞尺度钙信号+电活动	钙瞬态信号与激发时间序列
基于视觉姿态重建的运动量化方法	Vicon有标记光学运动捕捉 ^[67-69]	体表反光贴片三维坐标	三维关节坐标、关节角度
	Vicon+IMU混合采集 ^[69]	光学追踪+惯性单元信号	6自由度刚体位姿(位置+姿态)
	OpenPose ^[73]	多动物群体行为	2D关键点坐标
	HRNet ^[74]	高分辨率表征	高分辨率2D关键点
	AlphaTracker ^[75]	小样本、罕见姿态	关键点(适合小数据集)
	DeepLabCut(DLC) ^[70]	二维/三维关键点	2D/3D关键点坐标
	Anipose ^[42]	多视角成像	3D关键点+三角剖分位姿
	SLEAP ^[76]	单视角二维关键点	2D关键点坐标
多模态评估方法	MotorBox/MotoRater ^[80]	DLC无标记追踪+BMS行为学同步	行为评分+关节三维轨迹+步态不对称指数
	皮层-脊髓-外周-肌群多位点同步记录 ^[53]	皮层神经元锋电位、脊髓局部场电位、坐骨神经场电位、下肢肌群肌电信号、二维关节角度变化轨迹	锋电位+局部场电位+多肌群肌电+步态轨迹
	多通道同步触发硬件平台 ^[65,79]	统一时钟毫秒级多源对齐	多源数据时间同步标记、对齐事件流
	双光子钙成像+电生理+行为同步记录 ^[61]	钙信号+皮层神经元锋电位+自由活动行为	钙瞬态、电活动、行为轨迹三模态时序对应数据
	不完全脊髓损伤患者多模态步态与肌电评估系统 ^[81]	三维步态+表面肌电+ISNCSCI神经功能评分	三维步态参数+表面肌电活动+临床功能评分

经典行为学方法及单一电生理检测具备操作简便、设备成本低等实用优势,长期以来是脊髓损伤啮齿类模型基础评价的常规手段。但该类单一评估模式短板突出:量化精细度不足,多源数据时序割裂。既难以区分损伤后真实神经修复与单纯行为代偿^[12,26],也难以实现不同治疗方案之间标准化横向疗效对比。基于视觉姿态重建的运动量化方法可有效规避人工评判误差^[42,65],精准捕捉传统手段无法识别的细微肢体畸形与步态失衡,成为弥补传统评估缺陷的重要前沿方向。然而,仅依靠视觉姿态重建仍只能反映体表运动特征,无法同步解析脊髓、肌群内源神经电活动^[53],单一模态观测依旧存在维度缺失问题。

在此基础上,本文阐释了时序同步、多维互证的多模态整合评估框架的构建逻辑与技术基础,结合现有基础与临床研究实例论证了运动学-电生理同

步联用的协同增益^[53,81]。多模态交叉校验可有效降低疗效误判,实现毫秒级时序匹配,进而解析神经环路与步态的动态调控关系^[66,80]。多维度同步观测可区分干预效应,弥补单一检测维度缺失、时序脱节的核心缺陷。同时,本文客观梳理了现阶段多模态体系落地面临的现实瓶颈,包括视觉追踪跨实验室重复性差、行业统一数据规范缺失^[84]与高维多源时序数据配套分析工具匮乏等现实瓶颈。

综上所述,本文系统梳理了啮齿类脊髓损伤模型运动功能评估方法从经典行为学量表、电生理检测到深度学习姿态重建的发展脉络,并重点阐述了多模态同步整合评估框架的协同优势。值得注意的是,啮齿类脊髓损伤研究涉及挫伤、压迫、横断、光化学和兴奋毒等多种造模方式,不同模型在损伤机制与恢复轨迹上差异显著,对评估方法的普适性提出了严峻考验^[17]。本文所综述的基于视觉姿态重建的

运动量化方法与多模态同步采集平台,聚焦于不同模型的共同点,如相同的关节活动受限、步态不对称、协调性下降与精细运动功能丢失的运动学表现和皮质脊髓束传导异常、脊髓反射通路重塑和肌群协同激活模式改变的电生理现象^[90],摆脱了不同模型对特定评分标准的依赖,实现了跨模型关节运动缺陷的统一量化与共性电生理参数的稳定提取,从而在不同造模方式间建立起可横向比较的量化标尺^[23]。这一框架的建立,使得同一套评估体系能够应对多类SCI模型的评价需求,为不同损伤特征对应的诊疗方案筛选与复杂临床病例的综合治疗设计提供了方法学基础^[91]。

展望未来,本领域评估体系的完善可从3方面持续推进:第一,建立统一的啮齿类脊髓损伤多模态数据集、采集规范与统计分析标准,通过多中心联合研究缩小实验室间实验偏差,实现不同研究数据集互通复用;第二,推动深度学习姿态重建、多通道无线电生理等多模态同步采集硬件与算法一体化开发,降低多模态平台搭建门槛,让同步联合评估在常规实验室普及;第三,开发适配高维时序数据的专用解析与可视化工具,挖掘神经放电、关节运动、功能恢复间的定量关联模型,实现损伤程度早期分层、最优干预时间窗口精准预判。长远来看,标准化多模态同步评估框架将持续提升脊髓损伤修复研究的客观性与可重复性,为再生医学、神经调控康复技术的临床转化提供稳定可靠的方法学支撑。

参考文献

- [1] Lu Y B, Shang Z Z, Zhang W, et al. Global, regional, and national burden of spinal cord injury from 1990 to 2021 and projections for 2050: a systematic analysis for the Global Burden of Disease 2021 study [J]. *Ageing Research Reviews*, 2025, 103: 102598.
- [2] Ganjeifar B, Yari D, Salmasi Z, et al. Recent advances in the treatment of spinal cord injury [J]. *Archives of Bone and Joint Surgery*, 2024, 12(6): 380-399.
- [3] Almeida F M D, Marques S A, Santos A C R, et al. Molecular approaches for spinal cord injury treatment [J]. *Neural Regeneration Research*, 2023, 18(1): 23-30.
- [4] Squair J W, Milano M, de Coucy A, et al. Recovery of walking after paralysis by regenerating characterized neurons to their natural target region [J]. *Science*, 2023, 381(6664): 1338-1345.
- [5] Yang R, Zhang Y, Kang J N, et al. Chondroitin sulfate proteoglycans revisited: its mechanism of generation and action for spinal cord injury [J]. *Aging and Disease*, 2024, 15(1): 153-168.
- [6] Tomé D, Almeida R D. The injured axon: intrinsic mechanisms driving axonal regeneration [J]. *Trends in Neurosciences*, 2024, 47(11): 875-891.
- [7] Safdarian M, Trinká E, Rahimi-Movaghar V, et al. Global, regional, and national burden of spinal cord injury, 1990-2019: a systematic analysis for the Global Burden of Disease Study 2019 [J]. *The Lancet Neurology*, 2023, 22(11): 1026-1047.
- [8] Zheng B H, Tuszynski M H. Regulation of axonal regeneration after mammalian spinal cord injury [J]. *Nature Reviews Molecular Cell Biology*, 2023, 24(6): 396-413.
- [9] Khaing Z Z, Chen J Y, Safarians G, et al. Clinical trials targeting secondary damage after traumatic spinal cord injury [J]. *International Journal of Molecular Sciences*, 2023, 24(4): 3824.
- [10] Song J Q, Lü B H, Chen W C, et al. Advances in 3D printing scaffolds for peripheral nerve and spinal cord injury repair [J]. *International Journal of Extreme Manufacturing*, 2023, 5(3): 032008.
- [11] Powell M P, Verma N, Sorensen E, et al. Epidural stimulation of the cervical spinal cord for post-stroke upper-limb paresis [J]. *Nature Medicine*, 2023, 29: 689-699.
- [12] Gaudio H A, Padmanabhan V, Landis W P, et al. A novel translational bioinformatics framework for facilitating multimodal data analyses in preclinical models of neurological injury [J]. *Scientific Reports*, 2024, 14: 30710.
- [13] Hu X, Xu W, Ren Y L, et al. Spinal cord injury: molecular mechanisms and therapeutic interventions [J]. *Signal Transduction and Targeted Therapy*, 2023, 8: 245.
- [14] Poulen G, Perrin F E. Advances in spinal cord injury: insights from non-human primates [J]. *Neural Regeneration Research*, 2024, 19(11): 2354-2364.
- [15] Ben Borgens R. Naturally occurring spinal injury in the dog as a model for humans [M]//Restoring function to the injured human spinal cord. Berlin, Heidelberg: Springer, 2003: 109-117.
- [16] Han B, Liang W S, Hai Y, et al. Elucidating the potential mechanisms underlying distraction spinal cord injury-associated neuroinflammation and apoptosis [J]. *Frontiers in Cell and Developmental Biology*, 2022, 10: 839313.
- [17] Liu F Z, Huang Y, Wang H. Rodent models of spinal cord injury: from pathology to application [J]. *Neurochemical Research*, 2023, 48(2): 340-361.

- [18] Das U, Kamble A, Mandal S, et al. Unveiling the best fit: comparative perspective on animal models used for chronic diseases [J]. *SN Comprehensive Clinical Medicine*, 2026, 8: 254.
- [19] Kalotra S, Kaur G. Neuromethods and assessment tools for traumatic spinal cord injury in rodents: a mini review[J]. *Injury*, 2025, 56(7): 112288.
- [20] Ma Y H, Chen H Y, Wei Q S, et al. Transcranial optogenetic stimulation promotes corticospinal tract axon regeneration to repair spinal cord injury by activating the JAK2/STAT3 pathway[J]. *Neurospine*, 2025, 22 (2): 311-328.
- [21] Nardone R, Florea C, Höller Y, et al. Rodent, large animal and non-human primate models of spinal cord injury[J]. *Zoology*, 2017, 123: 101-114.
- [22] Courtine G, Bunge M B, Fawcett J W, et al. Can experiments in nonhuman primates expedite the translation of treatments for spinal cord injury in humans?[J]. *Nature Medicine*, 2007, 13(5): 561-566.
- [23] Jones L A T, Field-Fote E C, Magnuson D, et al. Outcome measures in rodent models for spinal cord injury and their human correlates[J]. *Experimental Neurology*, 2025, 386: 115169.
- [24] Basso D M, Beattie M S, Bresnahan J C. A sensitive and reliable locomotor rating scale for open field testing in rats [J]. *Journal of Neurotrauma*, 1995, 12 (1) : 1-21.
- [25] Yu J I, Seo T B. The effects of weight- and non-weight-bearing exercise on corticospinal axon sprouting, regeneration-related proteins and functional recovery after spinal cord contusion[J]. *Journal of Exercise Rehabilitation*, 2024, 20(6): 213-219.
- [26] Basso D M, Fisher L C, Anderson A J, et al. Basso mouse scale for locomotion detects differences in recovery after spinal cord injury in five common mouse strains [J]. *Journal of Neurotrauma*, 2006, 23(5): 635-659.
- [27] Buchl S C, Kim H N, Hur B, et al. Delayed atorvastatin delivery promotes recovery after experimental spinal cord injury [J]. *Neurotherapeutics*, 2025, 22 (2) : e00517.
- [28] Zhang L, Yamada S, Nagoshi N, et al. Combining therapeutic strategies with rehabilitation improves motor recovery in animal models of spinal cord injury: a systematic review and meta-analysis [J]. *Annals of Physical and Rehabilitation Medicine*, 2025, 68 (3) : 101911.
- [29] Merkler D, Metz G A S, Raineteau O, et al. Locomotor recovery in spinal cord-injured rats treated with an antibody neutralizing the myelin-associated neurite growth inhibitor Nogo-A [J]. *The Journal of Neuroscience*, 2001, 21(10): 3665-3673.
- [30] Anjum A, Yazid M D, Daud M F, et al. Evaluation of neuroprotective and neuroregenerative potential of NeuroAiD™ II (MLC901) in a rat model of kainic acid-induced spinal cord injury[J]. *Molecular Neurobiology*, 2025, 62: 13060-13072.
- [31] Kunkel-Bagden E, Dai H N, Bregman B S. Methods to assess the development and recovery of locomotor function after spinal cord injury in rats[J]. *Experimental Neurology*, 1993, 119(2): 153-164.
- [32] Smith R R, Burke D A, Baldini A D, et al. The Louisville swim scale: a novel assessment of hindlimb function following spinal cord injury in adult rats[J]. *Journal of Neurotrauma*, 2006, 23(11): 1654-1670.
- [33] Timotius I K, Bieler L, Couillard-Despres S, et al. Combination of defined CatWalk gait parameters for predictive locomotion recovery in experimental spinal cord injury rat models[J]. *eNeuro*, 2021, 8(2): ENEURO.0497-20. 2021.
- [34] Koopmans G C, Deumens R, Honig W M M, et al. The assessment of locomotor function in spinal cord injured rats: the importance of objective analysis of coordination [J]. *Journal of Neurotrauma*, 2005, 22 (2) : 214-225.
- [35] de Medinaceli L, Freed W J, Wyatt R J. An index of the functional condition of rat sciatic nerve based on measurements made from walking tracks[J]. *Experimental Neurology*, 1982, 77(3): 634-643.
- [36] Isidro A F, Medeiros A M, Martins I, et al. Using the MouseWalker to quantify locomotor dysfunction in a mouse model of spinal cord injury[J]. *Journal of Visualized Experiments*, 2023(193): e65207.
- [37] Hamers F P T, Lankhorst A J, van Laar T J, et al. Automated quantitative gait analysis during overground locomotion in the rat: its application to spinal cord contusion and transection injuries [J]. *Journal of Neurotrauma*, 2001, 18(2): 187-201.
- [38] Liu S, Wu Q, Wang L Y, et al. Coordination function index: a novel indicator for assessing hindlimb locomotor recovery in spinal cord injury rats based on catwalk gait parameters [J]. *Behavioural Brain Research*, 2024, 459: 114765.
- [39] Amende I, Kale A, McCue S, et al. Gait dynamics in mouse models of Parkinson's disease and Huntington's disease[J]. *Journal of NeuroEngineering and Rehabilitation*, 2005, 2: 20.

- [40] Page J J, Almanza J R, Xiong S N, et al. Self-delivering mRNA inhibitors of MK2 improve outcomes after spinal cord injury [J]. *Journal of Neuroimmunology*, 2023, 379: 578103.
- [41] Zabarsky ZK, Dean GM, Luo TD, et al. Keratin biomaterials improve functional recovery in a rat spinal cord injury model[J]. *Spine*, 2021, 46(16): 1055-1062.
- [42] Pereira T D, Aldarondo D E, Willmore L, et al. Fast animal pose estimation using deep neural networks [J]. *Nature Methods*, 2019, 16: 117-125.
- [43] Anderson K D, Sharp K G, Hofstadter M, et al. Forelimb locomotor assessment scale (FLAS): novel assessment of forelimb dysfunction after cervical spinal cord injury [J]. *Experimental Neurology*, 2009, 220 (1): 23-33.
- [44] Metcalfe M, Steward O. PTEN deletion in spinal pathways via retrograde transduction with AAV-RG enhances forelimb motor recovery after cervical spinal cord injury; Sex differences and late-onset pathophysiology [J]. *Experimental Neurology*, 2023, 370: 114551.
- [45] Anderson K D, Gunawan A, Steward O. Quantitative assessment of forelimb motor function after cervical spinal cord injury in rats: relationship to the corticospinal tract [J]. *Experimental Neurology*, 2005, 194 (1): 161-174.
- [46] Schallert T, Fleming S M, Leasure J L, et al. CNS plasticity and assessment of forelimb sensorimotor outcome in unilateral rat models of stroke, cortical ablation, parkinsonism and spinal cord injury [J]. *Neuropharmacology*, 2000, 39(5): 777-787.
- [47] Freria C M, Graham L, Azimi A, et al. Adaptation of a cervical bilateral contusive spinal cord injury for study of skilled forelimb function[J]. *Experimental Neurology*, 2023, 360: 114275.
- [48] All A H, Wong K L, Al-Nashash H A. Characterization of contusive spinal cord injury by monitoring motor-evoked potential [J]. *Biomedicine*, 2024, 12 (11): 2548.
- [49] Maeda Y, Takeda M, Mitsuhashi T, et al. Longitudinal electrophysiological changes after mesenchymal stem cell transplantation in a spinal cord injury rat model[J]. *PLoS One*, 2022, 17(8): e0272526.
- [50] Beiriger J, Shandal V, Sunderlin J, et al. Somatosensory evoked potentials [M]//Intraoperative monitoring. Cham: Springer, 2022: 165-179.
- [51] Tysseling V M, Janes L, Imhoff R, et al. Design and evaluation of a chronic EMG multichannel detection system for long-term recordings of hindlimb muscles in behaving mice [J]. *Journal of Electromyography and Kinesiology*, 2013, 23(3): 531-539.
- [52] States G J R, Clark T, Burke D A, et al. Pedal reaction forces and electromyography responses indicate eccentric contractions during motorized cycling in a rat model of incomplete spinal cord injury[J]. *Journal of Neurotrauma*, 2025, 42(3-4): 316-332.
- [53] Lang Y R, Tang R Y, Liu Y F, et al. Multisite simultaneous neural recording of motor pathway in free-moving rats[J]. *Biosensors*, 2021, 11(12): 503.
- [54] Nierula B, Stephani T, Bailey E, et al. A multichannel electrophysiological approach to noninvasively and precisely record human spinal cord activity [J]. *PLoS Biology*, 2024, 22(10): e3002828.
- [55] Buzsáki G, Anastassiou C A, Koch C. The origin of extracellular fields and currents: EEG, ECoG, LFP and spikes[J]. *Nature Reviews Neuroscience*, 2012, 13 (6): 407-420.
- [56] Höller Y, Thomschewski A, Uhl A, et al. HD-EEG based classification of motor-imagery related activity in patients with spinal cord injury[J]. *Frontiers in Neurology*, 2018, 9: 955.
- [57] Younessi Heravi M A, Maghooli K, Nowshiravan Rahatabad F, et al. A new nonlinear autoregressive exogenous (NARX) -based intra-spinal stimulation approach to decode brain electrical activity for restoration of leg movement in spinally-injured rabbits [J]. *Basic and Clinical Neuroscience*, 2023, 14(1): 43-56.
- [58] Steinmetz N A, Aydin C, Lebedeva A, et al. Neuropixels 2.0: a miniaturized high-density probe for stable, long-term brain recordings[J]. *Science*, 2021, 372(6539): eabf4588.
- [59] Abbott J R, Jeakle E N, Haghighi P, et al. Planar amorphous silicon carbide microelectrode arrays for chronic recording in rat motor cortex[J]. *Biomaterials*, 2024, 308: 122543.
- [60] Neely R M, Piech D K, Santacruz S R, et al. Recent advances in neural dust: towards a neural interface platform [J]. *Current Opinion in Neurobiology*, 2018, 50: 64-71.
- [61] Stosiek C, Garaschuk O, Holthoff K, et al. *In vivo* two-photon calcium imaging of neuronal networks [J]. *Proceedings of the National Academy of Sciences of the United States of America*, 2003, 100(12): 7319-7324.
- [62] Deng J H, Sun C, Zheng Y, et al. *In vivo* imaging of the neuronal response to spinal cord injury: a narrative review [J]. *Neural Regeneration Research*, 2024, 19 (4): 811-817.

- [63] Grienberger C, Konnerth A. Imaging calcium in neurons [J]. *Neuron*, 2012, 73(5): 862-885.
- [64] Pereira T D, Shaevitz J W, Murthy M. Quantifying behavior to understand the brain[J]. *Nature Neuroscience*, 2020, 23(12): 1537-1549.
- [65] Windolf M, Götzen N, Morlock M. Systematic accuracy and precision analysis of video motion capturing systems—exemplified on the Vicon-460 system [J]. *Journal of Biomechanics*, 2008, 41(12): 2776-2780.
- [66] Mendes A C, Beloni L F K, Arisawa E Â L S, et al. Development and validation of equipment for kinematic and sensory-motor analysis of experimental spinal injury induced in rats [J]. *Medicina (Ribeirão Preto)*, 2025, 58(4): e-221597.
- [67] Ignatowska-Jankowska B M, Swaminathan L I, Turkki T H, et al. Accurate tracking of locomotory kinematics in mice moving freely in three-dimensional environments [J]. *eNeuro*, 2025, 12(6): ENEURO.0045-25. 2025.
- [68] Wallace M N, Berger J I, Hockley A, et al. Identifying tinnitus in mice by tracking the motion of body markers in response to an acoustic startle[J]. *Frontiers in Neuroscience*, 2024, 18: 1452450.
- [69] Stepanenko N, Dubko A. Motion tracking systems in rehabilitation: a comparative analysis of sensor technologies, algorithmic methods, and clinical relevance [J]. *International Science Journal of Engineering & Agriculture*, 2025, 4(6): 72-100.
- [70] Mathis A, Mamidanna P, Cury K M, et al. DeepLabCut: markerless pose estimation of user-defined body parts with deep learning [J]. *Nature Neuroscience*, 2018, 21(9): 1281-1289.
- [71] Duque D H, Racca J M, Manzanera Esteve I V, et al. Machine-learning-based video analysis of grasping behavior during recovery from cervical spinal cord injury [J]. *Behavioural Brain Research*, 2023, 443: 114150.
- [72] Duque D H, Yang P F, Gore J C, et al. AI-assisted 3D analysis of grasping and reaching behavior of squirrel monkeys during recovery from cervical spinal cord injury [J]. *Behavioural Brain Research*, 2025, 476: 115265.
- [73] Cao Z, Hidalgo G, Simon T, et al. OpenPose: real-time multi-person 2D pose estimation using part affinity fields [J]. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 2021, 43(1): 172-186.
- [74] Sun K, Xiao B, Liu D, et al. Deep high-resolution representation learning for human pose estimation[C]//2019 IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR). June 15-20, 2019, Long Beach, CA, USA. IEEE, 2019: 5686-5696.
- [75] Chen Z X, Zhang R H, Fang H S, et al. AlphaTracker: a multi-animal tracking and behavioral analysis tool[J]. *Frontiers in Behavioral Neuroscience*, 2023, 17: 1111908.
- [76] Pereira T D, Tabris N, Matsliah A, et al. SLEAP: a deep learning system for multi-animal pose tracking[J]. *Nature Methods*, 2022, 19(4): 486-495.
- [77] Gosztolai A, Günel S, Lobato-Rios V, et al. Lift-Pose3D, a deep learning-based approach for transforming two-dimensional to three-dimensional poses in laboratory animals[J]. *Nature Methods*, 2021, 18(8): 975-981.
- [78] Bandres M F, Gomes J L, Moreno Romero G N, et al. Precision neuromodulation: promises and challenges of spinal stimulation for multi-modal rehabilitation[J]. *Frontiers in Rehabilitation Sciences*, 2023, 4: 1135593.
- [79] Mathis A, Schneider S, Lauer J, et al. A primer on motion capture with deep learning: principles, pitfalls, and perspectives[J]. *Neuron*, 2020, 108(1): 44-65.
- [80] Ascona M C, Tieu E K, Gonzalez-Vega E, et al. A deep learning-based approach for unbiased kinematic analysis in CNS injury [J]. *Experimental Neurology*, 2024, 381: 114944.
- [81] Liu W, Yang F, Yao Q, et al. A study on gait and muscle activation characteristics of persons with incomplete spinal cord injury with respect to age stratification [J]. *Frontiers in Bioengineering and Biotechnology*, 2026, 14: 1743995.
- [82] Walden K, Schuld C, Noonan V K, et al. Computer international standards for neurological classification of spinal cord injury (ISNCSCI) algorithms: a review[J]. *Spinal Cord*, 2023, 61(2): 125-132.
- [83] Shimizu T, Inomata K, Suda K, et al. A multimodal machine learning model integrating clinical and MRI data for predicting neurological outcomes following surgical treatment for cervical spinal cord injury [J]. *European Spine Journal*, 2025, 34(9): 3747-3755.
- [84] Fedor B A, Torres-Espin A, Vavrek R, et al. A community effort to develop common data elements for pre-clinical spinal cord injury research[J]. *Neurotrauma Reports*, 2025, 6(1): 391-401.
- [85] Iwama S, Takemi M, Eguchi R, et al. Two common issues in synchronized multimodal recordings with EEG: Jitter and latency [J]. *Neuroscience Research*, 2024, 203: 1-7.
- [86] Sheoran A, Fond K A, Davis L M, et al. Data reporting quality and semantic interoperability increase with community-based data elements (CoDEs). Analysis of the open data commons for spinal cord injury (ODC-SCI)

- [J]. *Experimental Neurology*, 2025, 385: 115100.
- [87] Noonan V K, Humphreys S, Biering-Sørensen F, et al. Enhancing data standards to advance translation in spinal cord injury[J]. *Experimental Neurology*, 2025, 384: 115048.
- [88] Jobbins S S, Pande V, Zeng C W, et al. Unbiased quantification of persistent postural and motor deficits following spinal cord injury in mice[J]. *PLoS One*, 2026, 21(3): e0343998.
- [89] Park S G, Mun S B, Kim Y J, et al. Development of machine learning models for gait-based classification of incomplete spinal cord injuries and cauda equina syndrome[J]. *Scientific Reports*, 2025, 15: 20012.
- [90] Shevtsova N A, Lockhart A B, Rybak I A, et al. Linking spinal circuit reorganization to recovery after thoracic spinal cord injury[J]. *eLife*, 2026, 14: RP107480.
- [91] Hassan O I, Takamiya S, Asgarihafshejani A, et al. Bridging the gap: a translational perspective in spinal cord injury[J]. *Experimental Biology and Medicine*, 2024, 249: 10266.