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手术机器人的临床应用进展

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摘　要

手术机器人(surgical robot)凭借精准化、微创化、智能化核心优势，已成为推动外科诊疗转型升级的关键技术，在泌尿外科、骨科、普外科、妇科、胸外科、神经外科等多专科广泛应用。本文综述了手术机器人的发展历程、主流类型与核心技术特点，全面梳理其在各临床专科的应用现状与优势，阐述远程手术的应用价值与技术支撑，分析当前核心技术垄断、成本高昂、规范化体系不完善等瓶颈挑战，并对智能化升级、国产突破、应用拓展、标准建立等未来方向进行展望，旨在为手术机器人的临床应用与发展方向提供全面参考。

关键词

手术机器人，微创手术，机器人辅助手术，临床应用，腹腔镜

Progress in Clinical Application of Surgical Robot

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Abstract

Surgical robots, characterized by core strengths in precision, minimal invasiveness, and intelligence,

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have emerged as a pivotal technology driving the transformation and upgrading of surgical diagnosis and treatment. They are extensively applied across numerous clinical specialties, including urology, orthopedics, general surgery, gynecology, thoracic surgery, and neurosurgery. This article reviews the developmental history, mainstream categories, and core technical features of surgical robots, comprehensively summarizes their current application status and clinical advantages in various disciplines, elaborates the application value and technical underpinnings of remote surgery, analyzes the prevailing bottlenecks and challenges such as core technology monopoly, high costs, and inadequate standardization systems, and prospects future directions including intelligent upgrading, domestic innovation, expanded application, and standardization establishment. This review aims to provide a comprehensive reference for the clinical application and developmental trends of surgical robots.

Keywords

Surgical Robot, Minimally Invasive Surgery, Robot-Assisted Procedures, Clinical Application, Laparoscopic

1. 引言

手术机器人是外科领域的一项创新技术，凭借其机械臂的高灵活性、高自由度、手术视野更清晰、切口更小等优势，目前已在临床上广泛应用。近年来，随着人工智能、5G、数字孪生等技术与手术机器人的深度融合，以及国产手术机器人的突破性发展，其临床应用范围不断拓展，已覆盖泌尿外科、骨科、普外科、妇科、胸外科、神经外科[1]等多个专科，成为推动外科诊疗向精准化、微创化、智能化转型的关键力量。本文旨在对国内外手术机器人的临床应用现状、核心突破及未来方向进行全面综述。

2. 发展历史

在手术中使用机器人的概念起源于 50 多年前，但直到 20 世纪 80 年代末才开始真正应用[2]。机器人在外科领域的应用最早可以追溯到 1988 年，Kwoh 等[3]的团队使用 PUMA 560 机器人系统对一名 52 岁男子进行了机器人辅助立体定向脑活检。

在 1991 年 Davies 等[4]使用该系统进行前列腺经尿道切除术，并促成了 PROBOT®的开发，其主要用于在通过超声扫描获得的前列腺预设虚拟重建模型中引导旋转刀片的运动，从而达到切除前列腺的目的[5]。然而，由于手术结束时需要对前列腺窝进行人工凝血，且由于当时技术受限，增生腺体的三维重建精度较差[6]，PROBOT® 的推广应用受到了限制[7]。然而，手术机器人的发展并未停滞，在骨科假体手术(Orthopedic Prosthetic Surgery)中的应用，ROBODOC® [8]成为首个获得美国食品药品监督管理局(FDA) 批准的手术机器人[9] [10]。

上述手术机器人均是在预设程序下运行的，然而由于外科手术的复杂性，外科手术机器人不适合全自动系统，其通常需要完全依赖外科医生的操作[11]。该类型的第一台手术机器人由斯坦福研究所(SRI) Parekattil [12]构思并研发，由两个独立部分组成，远程在场外科医生工作站(Telepresence Surgeon's Workstation, TSW)和远程手术单元(Remote Surgical Unit, RSU)组成。TSW 配备监视器和操作手柄，将信息传递给 RSU 的机械臂并进行操作，而 RSU 上配备微型摄像机，将实时画面传回给 TSW 反馈给术者[13]，这也

成为了现代手术机器人的雏形。SRI 系统并未打算商业化，而是作为研究原型，提供给军方用以远程医疗[14]。在 SRI 系统的基础上，2000 年随着第一代 daVinci®手术机器人的诞生及应用，其也逐渐成为现代手术机器人的主流[15]。

3. 主流手术机器人类型及核心技术特点

3.1. 腔镜手术机器人

腔镜手术机器人是目前全球应用最广泛、市场占比最高的类型[16] [17]，目前被广泛应用于泌尿外科、妇科、普外科、胸心外科等学科[18]。该系统通常由医师控制台、机械臂和影像系统组成[19]，核心作用是辅助医生完成各类微创手术。核心技术优势包括：解决了传统腹腔镜手术手眼不协调的问题；10~15 倍三维高清光学放大视野，可清晰呈现手术区域细微解剖结构；拥有 7 个自由度[20]，超越人手的生理极限，可在狭小体腔内完成精细的分离、缝合与打结操作；最新的 da Vinci 5®内置震颤过滤功能，进一步提升操作稳定性[21]-[23]。

根据手术入路分类。该类型的机器人分为多孔和单孔两类。多孔手术机器人发展更完全，代表类型有 DaVinci Xi 等，采用多个切口完成手术治疗，操作简单，手术视野更为宽广。单孔手术机器人有 DaVinci SP [24]等，仅需要在患者体表打单一切口即可完成手术，患者的创伤更小且恢复快，并且其在高度聚集的狭窄空间进行手术有更多优势[25]。

3.2. 骨科手术机器人(Orthopedic Surgical Robots)

骨科手术机器人是近年来增速最快的细分领域，各种新型机器人类型众多，在关节、脊柱、创伤等多个亚专业均有应用[26]-[29]。骨科手术机器人主打“精准定位、减少损伤”，尤其适合老年患者和复杂骨科手术，可有效降低术后脱位、长短腿等并发症风险。

3.2.1. 关节外科手术机器人

人工关节置换术(Joint Arthroplasty)已经成为目前骨科主流的治疗手段，用于治疗累计关节的骨折、中重度骨关节炎、骨肿瘤[30]、先天性关节发育不良等疾病，术后能保留原本关节的活动功能，对生活影响小，对患者生活质量改善明显[31] [32]，其中全髋关节置换手术(Total Hip Arthroplasty, THA)和全膝关节置换手术(Total Knee Arthroplasty, TKA)是最为常见的 2 种手术方式[33]-[35]。准确的关节假体植入对于预防短期和长期并发症至关重要。外科医生在手术过程中常常难以清晰地定位解剖结构，可能导致判断失误[36]。

在关节置换手术中，代表性的机器人为美国史塞克公司研发的 MAKO 智能机器人辅助系统(Mako SmartRoboticsTM System, MAKO)，其是一种半主动式关节置换术机器人辅助系统，基于 CT 进行三维(3 Dimensions, 3D)智能建模，可以提供更精确的定位[37]，通过术前规划与术中实时导航，精准控制假体植入的角度和位置[38]，降低假体松动、脱位等远期并发症风险，同时减少手术创伤，缩短患者术后康复时间[39]，符合加速康复外科(Enhanced Recovery after Surgery, ERAS)理念[40] [41]。并且机器人在复杂的人工关节置换术中也有良好的治疗效果[42]。

3.2.2. 脊柱外科手术机器人

脊柱的解剖结构复杂，走行众多神经、血管，且手术空间狭小，手术难度大[43] [44]。全球每年进行超过 483 万例脊柱手术[45]，为了优化和提升手术效果，机器人辅助系统已在全球范围内开发并部署。

在机器人辅助脊柱手术(Robotic Spine Surgery)中，机器人技术已被用于脊柱融合和器械植入[46]等手术，因为它有助于术中导航、轨迹确定[47]和螺钉植入[48]。并且机器人的使用也可减少患者和医务人员

的辐射暴露[49] [50]。

首款脊柱机器人 SpineAssist® (Mazor Robotics Ltd., Caesarea, Israel)于 2004 年获得 FDA 批准[51]，主要用来提高辅助置入椎弓根螺钉的精确度，至今仍是最广泛使用的机器人之一。Renaissance®是 Mazor 的第二代脊柱机器人，于 2011 年取代了 SpineAssist，其辅助椎弓根螺钉置入准确性高于传统手术、置钉时间短、安全性高。ROSA® BRAIN Robot (Zimmer Biomet Robotics, Montpellier, France)最初被设计用于颅骨手术，改进后于 2016 年获得 FDA 批准用于脊柱手术，该机器人能够随着患者的呼吸和手术操作而移动[52] [53]，在脊柱外科领域具有巨大潜力。Excelsius GPS® (Globus Medical, Inc., Audubon, Pennsylvania)于 2017 年获得 FDA 批准，其具有实时器械跟踪功能[54]，辅助脊柱手术的螺钉放置成功率更高[55]。

4. 临床应用

4.1. 普外科

作为手术机器人应用最广泛的领域，其已成为普外科精准微创的主流技术，在胃肠[56]、肝胆胰[57] [58]、疝与腹壁外科[59]等领域应用成熟，近年以单孔化[60] [61]、智能融合、复杂术式拓展为核心进展，临床获益与技术边界持续突破。

目前国内外的众多研究表明在直肠癌(Rectal Cancer)手术中机器人具有显著的优势[62]-[65]。Feng 等[66]通过临床对照研究首次证实机器人手术对比腹腔镜手术显著减少中低位直肠癌术后局部复发。Kojima 等[67]的研究对比传统腹腔镜，发现机器人辅助下其具有更低发生大便失禁和肠道功能障碍的概率。Feroci 等[68]的研究发现机器人辅助在淋巴结清扫方面显著优于传统腹腔镜手术。并且机器人直肠癌根治术具有更低的手术并发症发生率、更短的住院周期[69]以及更低的复发率[70]。得益于机器人更好的手术视野和自由度，其在超低位直肠癌保肛手术中对比腹腔镜具有良好的效果[71] [72]，在复杂直肠癌手术中的应用也是安全可行的[73]。

胰十二指肠切除术(Pancreaticoduodenectomy, PD)被认为是普外科最具挑战性的手术之一，因为术中出血及包括胰瘘在内的术后并发症带来了高风险的术后发病率和死亡率[74] [75]。由于 PD 的复杂性致使其更适合机器人手术。2003 年 Giulianotti 等[76]报告了首例机器人胰十二指肠切除术(Robotic Pancreaticoduodenectomy, RPD)。对比腹腔镜以及传统的开放，RPD 能改善切除切缘和淋巴结摘取数量[77]，减少失血量[78]、伤口感染率更低[79]、住院时间缩短[80]，但手术时间更长[75]。并且由于机器人操作的高灵活度以及稳定性，其可用于复杂的 PD [81]以及特殊类型的 PD。Yang 等[82]将 RPD 应用与肥胖患者并取得了良好的效果。随着操作技术以及术者熟练度的提高，甚至可以减少打孔数量[83]从而进一步减小创伤。

4.2. 泌尿外科

腹腔镜手术是泌尿外科疾病治疗的重要手段之一[84]，但由于泌尿外科手术操作空间狭小、结构复杂的区域，且伴有术者身体动作、肌肉疲劳等因素，操作精准度和视野清晰度会受到影响[85]。对比传统腹腔镜，手术机器人系统可以为医生提供更好的手术操作条件，使患者得到的治疗更安全、精准，不仅有利于提高手术效率、缩短手术时间[86] [87]。

泌尿外科作为手术机器人应用最成熟、最广泛的领域[88]，在多种泌尿外科手术的应用中均取得了良好的效果。在前列腺癌(Prostate Cancer)根治术中，机器人辅助腹腔镜前列腺癌根治术(Robot-Assisted Laparoscopic Radical Prostatectomy, RALP)能更好地保护前列腺周围的神经血管束[89]、减少术中出血[90]、降低术后尿失禁[91] [92]、勃起功能障碍[93]等并发症[94]。在机器人辅助肾部分切除术(Robot-Assisted Partialnephrectomy, RAPN)中，其在围手术期安全性方面优势显著[95]，使复杂肿瘤的切除与缝合更为可靠[96]，但其在手术时间方面会高于传统开腹手术[97]，需要术者提高熟练度以解决。

4.3. 胸外科

胸外科亦是手术机器人应用发展迅速、适应证不断拓展的核心领域。机器人辅助胸外科手术(Robotic-Assisted Thoracic Surgery, RATS)，主要应用于肺癌的肺叶/肺段切除术、食管癌根治术以及复杂的纵隔肿瘤切除术等[98]。其在肺癌的淋巴结清扫、复杂纵隔肿瘤[99]、食管癌根治术[100]中均表现出更低的术中出血、并发症水平以及更低的复发率等。但其在手术时间方面略长于传统胸腔镜手术，需通过术者熟练度提升予以优化[101]。

4.4. 骨科

骨科手术机器人的应用主要集中于关节置换和脊柱手术两大场景，有效解决了传统骨科手术精度不足、创伤较大的问题。在关节置换手术中，机器人可通过术前规划与术中实时导航，精准控制假体植入的角度和位置，降低假体松动、脱位等远期并发症风险，同时减少手术创伤，缩短患者术后康复时间[38] [102]。MAKO 机器人辅助关节置换术，可将假体定位误差控制在 0.5 mm 以内，术后患者能更快下地、更快恢复[39]。在脊柱手术中，机器人可精准完成椎弓根螺钉植入、椎板切除等操作，避免损伤脊髓和神经根[103] [104]，尤其适用于复杂脊柱畸形、脊柱肿瘤等手术[105]。

临床主流的 MAKO 与 ROSA 骨科机器人在技术特性上差异显著。MAKO 为半主动操作系统，凭借触觉反馈实现操作边界自动限制，假体置入精度把控更严苛；ROSA 则以术中导航导板定位为核心，影像适配性更强、操作更灵活，二者在学习曲线、手术适配场景上各有侧重，也为临床术式选择提供了不同参考[38]。

5. 机器人远程医疗

机器人远程手术(Robotic Telesurgery)指的是对手术机器人的远程控制完成手术[106]。传统远程会诊仅能实现影像判读与诊疗建议，难以实时手术操作。随着 5G 通信技术的发展，手术机器人突破地理限制为均衡优质医疗资源提供重要的发展方向。其成功运行主要依赖于三大核心部分的精密协同：患者端手术单元、高速可靠的网络传输层和医生端控制中心。

多项指南与专家共识已证明机器人远程手术的可行性[107]-[109]。其为医疗资源匮乏的地区提供高质量手术[110]，允许不同医疗中心的外科医生实时进行外科协作[111] [112]，消除患者长途转运经济负担和危险[113]。

但目前仍需要关注一些关键问题：设备的可靠性、网络传输的稳定性、紧急状况处置预案、手术责任的划分以及伦理及知情同意流程的完善等[114]。

随着 5G/6G 通信网络的发展，其能进一步提升画面传输的稳定性和实时性，突破远程手术的地理限制，实现跨洲际手术操作；结合 AI 通过机器学习模型对风险预警预测[115]。

6. 手术机器人临床应用的现存瓶颈与挑战

尽管手术机器人在临床应用中取得了显著进展，但其普及和发展仍面临诸多瓶颈与挑战。

目前，全球手术机器人核心技术仍被少数进口企业垄断[116]，国产机器人在高端核心部件(如高精度机械臂、三维成像系统、力反馈系统)上仍存在短板。多数手术机器人缺乏真实的力反馈功能，医生无法通过操作感受到组织的硬度和阻力，可能增加术中组织损伤的风险。

同时手术机器人的购置成本、维护成本及耗材成本均较高，导致是制约其在临床普及的重要因素。由于其高昂的手术费导致许多患者在面临选择时望而却步，仍然选择传统手术方式[117]。

并且由于手术机器人普及度并不广泛，其临床应用的规范化体系尚未完全建立，缺乏统一的手术适

应症、操作流程和疗效评价标准。部分术式的长期临床疗效数据不足，难以充分证明其优于传统手术的长期价值。

7. 总结与展望

手术机器人作为现代外科的重要创新成果凭借精准化、微创化、智能化的核心优势，已在多个临床专科实现广泛应用。相较于传统腹腔镜及开放手术，其具有更小的手术创伤、更干净的淋巴结清扫、更小的术中出血量及更少的并发症等，显著提升了手术疗效和患者预后。

未来随着通信及 AI 技术的发展，手术机器人技术向智能化、精准化升级，实现术中图像导航、手术流程自动识别(Surgical Phase Recognition)、器械自主跟踪或实现部分手术步骤的自动化；并且越来越多的国产厂家的加入，有望打破海外厂家垄断的地步，进一步降低价格，加速其推广；随着越来越多的临床证据，其临床应用范围会进一步拓展；并且还需要建立完善的相关专门人才培养体系，解决专业研发人员及术者的短缺问题；同时还需要进一步建立更多的专家共识与指南规范其操作，从而推动其在临床治疗领域的更大应用价值。

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