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Design and experimental verification of a portable multi-degree-of-freedom electric needle holder

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Highlights

- Innovative Design: A wire-driven multi-degree-of-freedom electric needle holder enhances laparoscopic suturing flexibility and stability.
- Advanced Motion Control: Two rotational joints enable yaw and pitch movements for precise needle placement in confined spaces.
- Superior Clamping Performance: With a maximum clamping force of 29.6 N an extraction force of 12.9 N, the needle holder prevents slippage.
- 28% Faster Suturing: Reduced operation time due to minimized repositioning in complex procedures.
- Clinical Potential: Validated through diverse tests, demonstrating accuracy and efficiency in minimally invasive surgery.

Abstract

Objective: To design and validate a portable multi-degree-of-freedom electric needle holder to improve operational flexibility and precision in laparoscopic surgery, while reducing the operator's workload. The design optimizes the transmission system to enable precise control of surgical instruments, addressing the challenges of complex surgical environments. **Methods:** A multi-degree-of-freedom transmission structure, driven by steel wires, was designed. It integrates motors and angle sensors to achieve multi-directional rotation and force control for the grasping forceps. The experimental section includes tests for maximum gripping force, maximum extraction force, and a porcine suturing experiment. The performance of the electric needle holder was compared with traditional needle holders in simulated laparoscopic surgery to verify its effectiveness. **Results:** Experimental results show that the maximum gripping force of the electric needle holder at various angles reached 29.6 N, significantly higher than that of traditional needle holders. The maximum extraction force for needles of different sizes is approximately 12.9 N, effectively preventing needle slippage. Additionally, the porcine suturing experiment demonstrated that the electric needle holder significantly reduced operation time and improved suturing precision in complex surgical settings. **Conclusion:** The portable multi-degree-of-freedom electric needle holder enhances operational flexibility and safety in laparoscopic surgery by increasing the rotational degrees of freedom and precise motor control. Its superior gripping force and operational efficiency suggest strong clinical potential, offering significant improvements over traditional surgical instruments.

Keywords: Needle holder, multi-degree-of-freedom, motor-driven, portable, structural design

Introduction

Laparoscopic surgery is a minimally invasive technique that involves inserting instruments through small incisions and using real-time imaging from an endoscope to guide precise operations. It is considered one of the most significant advancements in surgery in the 20th century. Traditional laparoscopic procedures typically require 3 to 5 small incisions, ranging from 5 to 20 millimeters in size. In contrast, Single-Incision Laparoscopic Surgery offers a less invasive alternative, with several potential advantages, including reduced postoperative pain, shorter recovery time, and improved cosmetic outcomes [1].

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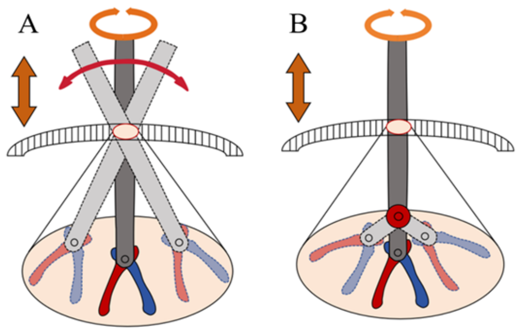

Figure 1. Comparison of Degrees of Freedom in Different Needle Holders. (A) Traditional Needle Holder; (B) Multi-Degree-of-Freedom Needle Holder.

However, Single-Incision Laparoscopic Surgery still faces technical challenges, such as instrument collisions, lack of appropriate triangulation, and difficulty in tissue retraction [2, 3].

The needle holder is a key instrument in Single-Incision Laparoscopic Surgery. As an indispensable tool during suturing, it is used to clamp and control the suture needle, enabling complex suturing operations within the confined space of the surgical field. Given the limited operating space in minimally invasive surgery, the instrument's degrees of freedom (DOF) and stability are critical for procedural success [4]. An ideal needle holder should provide high-precision control within the narrow surgical view while maintaining sufficient stability to ensure the quality of suturing. However, traditional rigid needle holders have limitations due to their restricted DOF, leading to longer surgical times and steeper learning curves [5, 6]. **Figure 1** compares the operating modes of traditional needle holders and multi-degree-of-freedom needle holders. Therefore, the development of multi-degree-of-freedom needle holders has become a primary approach to improving both surgical efficiency and the learning curve [7].

Wire-driven mechanisms, with their low inertia, lightweight design, and high precision, are well-suited for long-distance transmission in confined spaces [8-10]. Consequently, most existing multi-degree-of-freedom instruments employ wire drive systems, which can be broadly classified into two categories: rigid structures that form rotational joints through interconnected links, and flexible integrated structures that achieve bending through material deformation. Examples of the first category include the RealHand instrument developed by Novare Surgical System, the Hand-X instrument developed by Human Extension, and handheld instruments used in robotic systems such as the da Vinci surgical robot [11-13]. The second category includes instruments like the Autonomy Lapro-Angle developed by Cambridge Endo [14]. While wire-driven systems offer advantages such as being lightweight and cost-effective, the holding force applied by the operator can lead to wire deformation, requiring greater force to drive the tool's end-effector, which can result in operator fatigue [15, 16].

To address these challenges, this study proposes a novel multi-degree-of-freedom electric needle holder. The proposed needle holder features a compact wire-driven joint structure and utilizes an electric motor to provide the clamping force, enabling precise multi-degree-of-freedom control and enhancing operational comfort. This paper presents the design principles, key technologies, and functional validation results of the proposed electric needle holder.

Materials and methods

Design principles of the needle holder

Traditional needle holders typically consist of a rigid long shaft, an end clamp, and a handle, providing two DOF: axial insertion and rotation. Due to the limited DOF and confined working space, movements such as yaw and pitch rely heavily on the operator's large-arm motions, which are achieved through leverage [17]. Additionally, the rotation direction of the needle holder is opposite to that of the operator's arm movements, meaning that reaching the desired position with the instrument often requires considerable time and practice. This operating method not only increases the risk of interference between instruments but can also cause secondary damage to the patient's incision.

In certain surgical procedures, instruments must maneuver around organs, requiring the end-effector to possess a wide range of motion and large-angle directional adaptability. Traditional needle holders, limited to two DOF—axial insertion and rotation—force operators to rely on arm movements for adjustments, increasing the risk of collisions and procedural complexity. To address these challenges, the proposed needle holder integrates a front-end mechanical joint, introducing two additional DOF (yaw and pitch). This expands the total DOF to four (axial insertion, rotation, yaw, and pitch), allowing for precise needle angle adjustments in confined spaces. Compared to conventional instruments (2 DOF vs. 4 DOF), this design enhances the gripper's motion range, reduces collision risks, and improves suturing efficiency and safety by minimizing reliance on operator arm leverage.

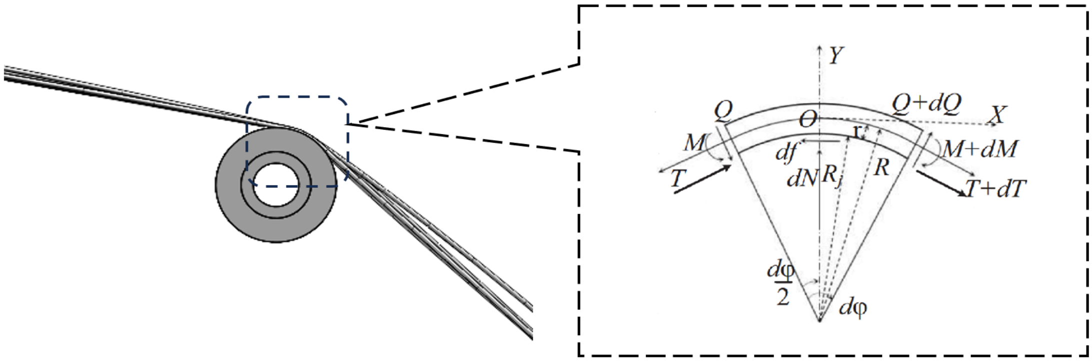

Figure 2. Force Analysis of the Infinitesimal Element of the Steel Wire.

Due to tension loss caused by the steel wire passing through the guide pulleys in a wire-driven pulley system, this loss directly affects the force and displacement transmission characteristics [18]. By conducting a force analysis on the infinitesimal elements of the steel wire, the tension transfer characteristics in a single-pulley system can serve as the foundation to derive the tension transmission characteristics throughout the entire drive system.

Figure 2 shows the force analysis diagram at the contact point between the steel wire and pulley. In the force transmission process, the steel wire possesses elasticity and bending stiffness. Therefore, when modeling, it is necessary to account for the elastic deformation, shear force, and bending moment of the steel wire. By establishing the force equilibrium equations along the X and Y axes and the force and moment equilibrium equations around point O, the following equation can be derived:

$$\begin{cases} \sum F_x = (T+dT)\cos\frac{d\varphi}{2} - T\cos\frac{d\varphi}{2} + (Q+dQ)\sin\frac{d\varphi}{2} + Q\sin\frac{d\varphi}{2} - df = 0 \\ \sum F_Y = (Q+dQ)\cos\frac{d\varphi}{2} - Q\cos\frac{d\varphi}{2} - (T+dT)\sin\frac{d\varphi}{2} - T\sin\frac{d\varphi}{2} + dN = 0 \\ \sum M_O = (M+dM) - M - (Q+dQ)\frac{R\,d\varphi}{2} - Q\frac{R\,d\varphi}{2} + r\,df = 0 \end{cases} \quad (1)$$

Where T is the tension in the steel wire; Q is the shear force in the steel wire; M is the bending moment in the steel wire; N is the normal force at the contact surface of the steel wire; f is the Coulomb frictional force at the contact surface of the steel wire; r is the radius of the steel wire; R is the sum of the radius of the guide pulley and the radius of the steel wire; and φ is the wrap angle at the contact surface of the steel wire. Since the diameter of the steel wire is typically small, its bending stiffness and radius are negligible, so it can be treated as a fine flexible rope. Therefore, $Q=M=0$ and $r=0$. When considering its nonlinear friction effects, the frictional force and normal pressure follow Amontons' law [19]:

$$f = \alpha N^n, n \leq 1 \quad (2)$$

Where α and n are constants that depend on the materials of the two contacting objects.

From the above derivation, the relationship between the input tension and output tension of the steel wire between the $i-1$ pulley and the i pulley can be expressed as:

$$T_{i-1,i} = \alpha\left[\left(\frac{T_{i,i+1}}{\alpha}\right)^{\frac{1-n}{n}} + \alpha(1-n)\varphi\right]^{\frac{n}{1-n}} \quad (3)$$

From the equation (3), it can be seen that when the materials of the steel wire and pulley remain unchanged, both α and n are constants. The primary factor influencing the frictional loss of the input tension is the wrap angle of the rope on the pulley. Therefore, when designing the transmission system, the contact angle between the steel wire and the pulley should be minimized to reduce frictional losses.

Drive system design of the needle holder

In laparoscopic surgery, the movements of the needle holder primarily involve two aspects: first, the rotational movement of the needle holder within the abdominal cavity for suturing operations; and second, the application of a strong clamping force to the suture needle to prevent relative displacement between the clamp and needle during suturing. Due to the limited operating space in the laparoscopic environment, a short-range, precise driving mechanism is essential. Among various drive and connection mechanisms, the wire-driven joint mechanism occupies less space and allows for precise control. Therefore, a wire-pulley system with two joints is adopted to drive the needle holder.

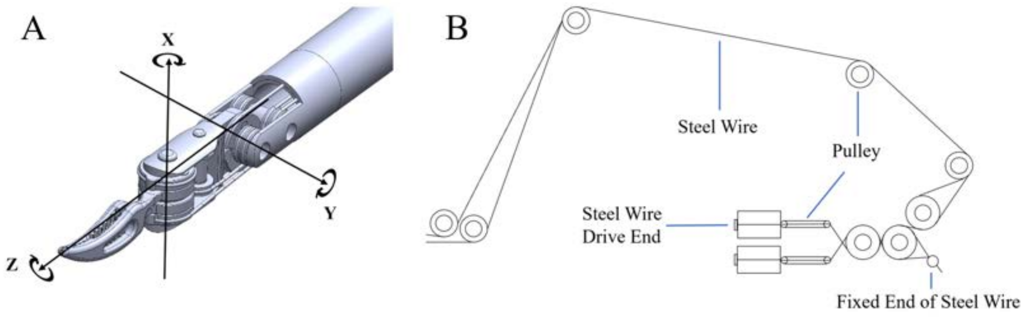

Figure 3. Needle Holder Structure. (A) Schematic Diagram of the Gripping Joint; (B) Steel Wire Drive System.

The schematic of the joint structure is shown in **Figure 3A**. Joint 1 rotates around the X-axis, while Joint 2 rotates around the Y-axis, simultaneously controlling the opening and closing of the gripper. Rotation along the Z-axis is achieved by rotating the entire instrument to prevent internal interference and wire entanglement. This mechanism provides two additional rotational DOF compared to traditional needle holders, granting the operator greater flexibility in performing laparoscopic procedures.

To align the rotational angles of the handle with the gripper and increase the handle's movement range, a long-distance driving mechanism using a specific steel wire transmission method was designed. The gripper's rotation is controlled by two joints. The first joint, controlling rotation in the XZ plane, uses two steel wires. One end of each wire is fixed, while the other end is connected to a driving pulley. When the handle rotates upward, one steel wire displaces under tension, controlling the gripper's rotation along the Y-axis. When the handle rotates downward, the other steel wire controls the reverse rotation. The second joint simultaneously controls the gripper's rotation in the YZ plane and its opening/closing motion, using two closed-loop steel wires. Each wire is fixed to both the driving and driven pulleys. The driving pulleys are fixed to the left and right grippers, enabling independent control. When the gripper rotates around the X-axis, the fixed axis of the driving pulley rotates, and the relative positions of the left and right grippers remain unchanged, rotating together.

For opening and closing the gripper, both grippers rotate, driving the rotation of the driving pulley, which in turn drives the steel wires and driven pulleys to rotate, causing the grippers to open and close. This design synchronizes the gripper's rotational angles with the operator's wrist movements, making the gripper more flexible and easier to control. **Figure 3B** presents a schematic diagram of the steel wire-pulley system structure. As the wrap angle of the pulley increases, the loss in output tension also increases. Therefore, minimizing the wrap angle in the steel wire drive system design is crucial while ensuring that the handle has sufficient movement space to guarantee the gripper's operational range. Based on these design requirements, the steel wire drive system shown in the figure uses multiple pulley sets to guide the input tension while minimizing the wrap angle to avoid exceeding 90°, thus reducing frictional losses.

Motion simulation of the needle holder

To prevent force transfer leading to steel wire deformation and insufficient clamping force, a kinematic simulation of the wire-pulley system was conducted using Automatic Dynamic Analysis of Mechanical Systems. In the simulation, components without relative displacement were treated as a single unit. Frictional and elastic contact were set between the gripper and the suture needle. A constant force ranging from 10 to 50 N was applied to the steel wire's end, and the resultant forces along the X and Y axes, as well as the resultant force, were obtained.

The simulation results showed a linear relationship between the clamping force and the operating force, with slopes of 0.016 and 0.188 for F_x and F_y respectively, and a resultant force slope of 0.19. It is evident that the system suffers significant force transmission losses. As the operator applies a larger force, the clamping force provided by the gripper decreases. This issue can lead to a significant load on the operator's hands during prolonged suturing. To address this, an electric motor was added to provide the clamping force, reducing operator hand fatigue.

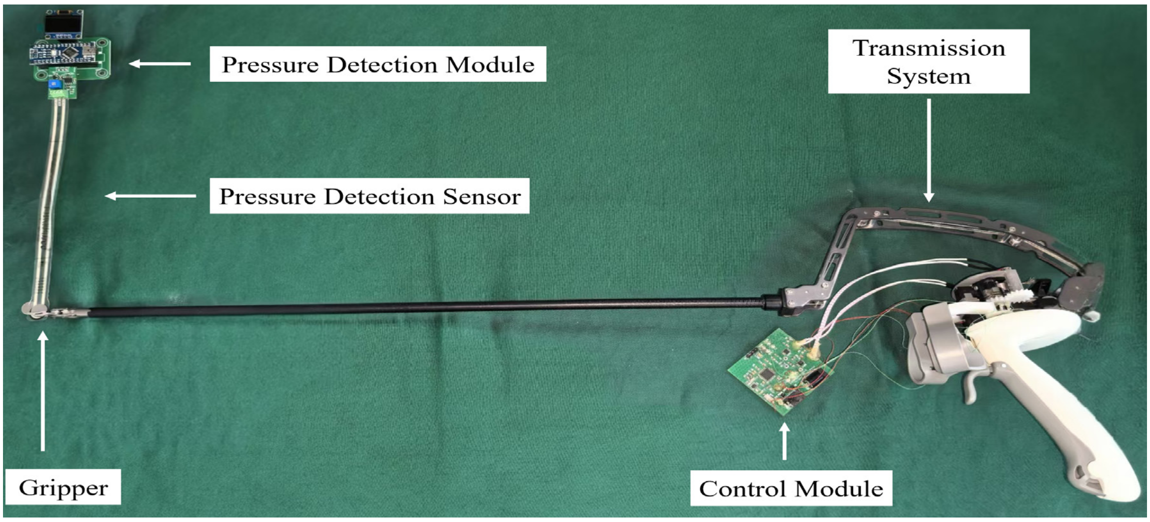

Figure 4. Maximum Clamping Force Experiment.

Needle holder circuit and control program design

A PIHER PT10 linear potentiometer was selected as the angle sensor, mounted on the handle with its central hexagonal hole matching the fixed shaft. As the handle rotates, the output resistance of the angle sensor changes, controlling the motor's forward/reverse rotation and speed, which in turn governs the movement of the gripper.

The motor drive and control are implemented through an H-bridge DC motor driver chip (DRV8832). The STM32F103CBT6 microcontroller (MCU) processes the analog signals from the angle sensor and generates PWM signals to control the motor's operation.

For the power supply design, considering that the system may share a power source with high-frequency devices such as electrosurgical tools, 220 V AC is converted to 5 V DC via a power adapter. A K7803-500 power module then converts the 5 V to 3.3 V to supply the MCU and motor driver chip.

To synchronize the rotational angle and speed of the gripper with the handle, the focus during programming was on controlling the Pulse Width Modulation (PWM) signal output from the MCU. As the resistance of the angle sensor increases, the MCU processes this analog signal, calculates the handle's rotation angle based on the slope of the resistance change, and outputs the corresponding PWM duty cycle to control the motor's forward rotation, causing the gripper to close. The motor speed is controlled by adjusting the PWM duty cycle. When the resistance of the angle sensor decreases, the MCU reverses the motor to open the gripper. Based on these functions, the circuit board design and motor control code were completed.

Experimental methodology for the needle holder

To comprehensively evaluate the performance of the multi-degree-of-freedom electric needle holder, three sets of experiments were designed: the maximum clamping force experiment, the maximum extraction force experiment, and the pork suturing experiment. Each experiment was repeated multiple times, and the data were averaged to reduce errors.

Maximum clamping force experiment

The maximum clamping force experiment aims to quantitatively assess the clamping ability of the multi-degree-of-freedom electric needle holder at different angles, providing scientific and quantitative data for its application in actual surgeries. A Flexiforce thin-film pressure sensor kit with a precision of 0.1 N was used to measure the maximum pressure exerted by the gripper on the suture needle.

Figure 4 displays the prototype of the multi-DoF electric needle holder and its maximum clamping force test setup. During the experiment, the deflection and pitch angles of the needle holder were adjusted, and measurements were taken every 10° within the range of -60° to 60°. This range covers the various operational angles the needle holder may encounter in actual surgeries, allowing for a comprehensive evaluation of its clamping performance at different postures. At each angle, the handle of the needle holder was rotated, causing the gripper to slowly close.

When the gripper completely clamps the sensor

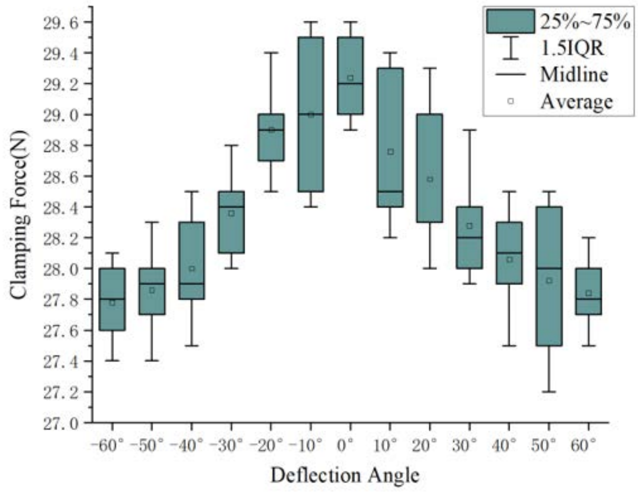

Figure 5. Clamping force at different deflection angles.

and the motor automatically stops due to the maximum clamping force being reached, the maximum clamping force displayed by the sensor was recorded.

Maximum extraction force experiment

The maximum extraction force experiment evaluates the maximum force the multi-degree-of-freedom electric needle holder can exert on the suture needle without causing it to slip out, when clamping different types of suture needles. This test indirectly measures the maximum resistance the suture needle can withstand and can be cross-validated with the maximum clamping force data, providing key insights into the needle holder's performance during actual surgeries. The experiment was conducted using an Instron 5900 tensile testing machine. The maximum force required to pull the suture needle out of the gripper, while securely clamped, was measured by gradually increasing the tensile force.

During the experiment, different types of suture needles were clamped in the needle holder's gripper to ensure the needle remained fixed after clamping. The needle holder was mounted on the tensile testing machine to maintain stability during testing. The machine was started, and the tensile force was gradually increased until the suture needle was completely pulled out, recording the maximum extraction force at this point.

Pork suturing experiment

The pork suturing experiment is designed to evaluate the usability and learning efficiency of the multi-degree-of-freedom electric needle holder during actual operations. The experiment involved two participants, both of whom had no prior experience using a needle holder. They were each tasked with performing suturing operations using both a traditional needle holder and the multi-degree-of-freedom electric needle holder. To ensure the comparability of the results, both participants received the same training before the experiment. Each participant practiced with the assigned needle holder for 10 hours to become familiar with the basic operation and feel of the tool.

After the practice session, the participants were asked to perform a real-world task using a laparoscopic surgery simulator: suturing a 5 cm length on a piece of pork and completing 10 standard surgical knots. This task simulated the suturing requirements encountered in surgery and served as an important metric for evaluating the needle holder's performance and ease of use. During the experiment, the time taken by each participant to complete the task and their subjective feedback were recorded. By comparing the performance of the two types of needle holders under the same conditions, the study assessed whether the multi-degree-of-freedom electric needle holder offered advantages in reducing operation time and improving learning efficiency.

Results

This study systematically evaluated the clamping force, extraction force, and suturing effectiveness of the multi-degree-of-freedom electric needle holder. The experimental results demonstrate that the device performs well in achieving stable clamping and improving suturing efficiency, meeting the expected design goals. The detailed analysis is as follows:

Maximum clamping force analysis

The maximum clamping force of the multi-degree-of-freedom electric needle holder varies at different angles. The experimental results show that when the gripper is at 0°, the maximum clamping force is 29.6 N. At a deflection angle of 60°, the clamping force decreases to a minimum of 27.2 N. **Figure 5** illustrates the maximum clamping force results under different gripping angles. As the deflection angle increases, the clamping force slightly decreases, likely due to changes in the lever arm of the gripper at larger deflection angles. Since the variation is small, it can be considered negligible in actu-

Table 1. Maximum Extraction Force (N) for Different Types of Suture Needles

Group	Diameter (mm) × Length (mm)				
	0.6×14	0.7×17	0.8×20	0.9×24	1.0×28
1	12.86	12.90	12.91	12.90	12.88
2	12.91	12.89	12.88	12.91	12.89
3	12.88	12.92	12.89	12.90	12.92

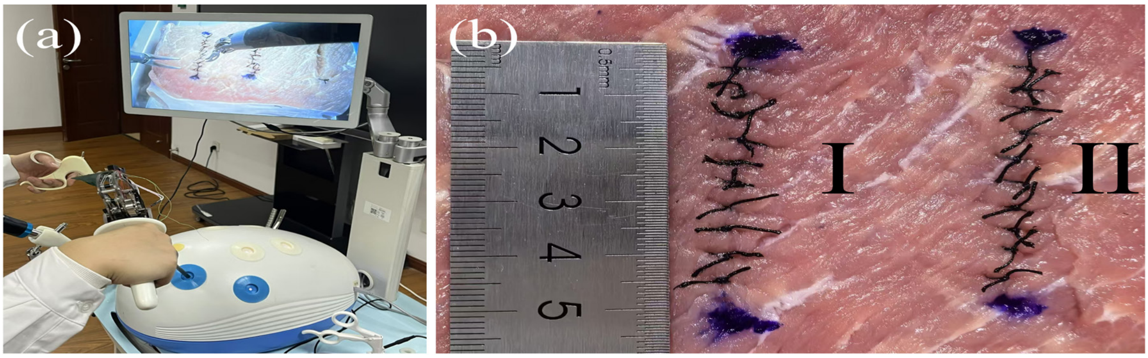

Figure 6. Pork Suturing Experiment. (a) Laparoscopic Surgery Simulation Training Scene; (b) Suturing Outcomes on Pork Tissue. I represents marks from the traditional needle holder; II represents marks from the multi-degree-of-freedom electric needle holder.

al operation.

For a conventional needle holder, the average clamping force required to securely hold the suture needle is 8.9 N [20]. In typical surgical operations, the clamping force of the gripper in the da Vinci system ranges from 7.77 to 19.94 N [21]. Therefore, the maximum clamping force of 29.6 N provided by the electric needle holder is much higher than the force needed to hold the suture needle. This indicates that the clamping force design of the electric needle holder fully meets the requirements for clamping at different angles during routine surgery, ensuring the needle's stability during suturing and reducing the risk of needle displacement or detachment.

Maximum extraction force analysis

The experimental data show that the maximum extraction force for various types of suture needles clamped by the multi-degree-of-freedom electric needle holder remains around 12.9 N. No significant difference in extraction force is observed across different types of suture needles under the same conditions. **Table 1** summarizes the maximum extraction forces when the multi-DoF electric needle holder grips suturing needles of different specifications. The extraction force is smaller than the clamping force, likely due to insufficient friction between the gripper and the suture needle. The force required for a suture needle to penetrate various tissues is typically below 2 N, which is much smaller than the extraction force of the needle holder [22]. This suggests that the extraction force of 12.9 N is more than sufficient to meet the demands of suturing during surgery, preventing the suture needle from being pulled out during the procedure. Furthermore, the uniformity of the extraction force demonstrates the needle holder's versatility in clamping different sizes of suture needles, showcasing its excellent adaptability. This is crucial for its widespread use in actual surgeries, as suture needle sizes vary across different types of procedures. The multi-size compatibility of the electric needle holder enhances its versatility and practicality.

Suturing efficiency analysis

In the pork suturing experiment, the average suturing time for the traditional needle holder group was 18 minutes, whereas the average time for the multi-degree-of-freedom electric needle holder group was reduced to 12 minutes. This significant time difference resulted in a roughly 28% improvement in suturing efficiency. **Figure 6** provides a comparative analysis of pork tissue suturing experiments. The primary reason for this improvement is the flexibility and multi-degree-of-freedom design of the electric needle holder, which allows the operator to adjust the angle of the suture needle without needing to reposition the needle holder. This significantly reduces the adjustment time during the procedure.

From the operators' subjective evaluations, the multi-degree-of-freedom electric needle holder was found to be easier to learn and more convenient to operate, effectively reducing hand fatigue. Particularly in complex suturing tasks, the time advantage of the electric needle holder was especially apparent. In situations that required frequent adjustments to the suture needle's angle, the electric needle holder reduced operational steps and increased suturing speed. Additionally, the smooth operation characteristics of the electric needle holder minimized hand fatigue, contributing to improved suturing quality and accuracy. This advantage is especially noticeable in long and complex surgeries, providing surgeons with a more comfortable operational experience and potentially increasing the surgery's success rate.

Discussion

The excellent performance of the multi-degree-of-freedom electric needle holder in terms of clamping force, withdrawal force, and operational efficiency highlights its significant advantages in meeting the demands of surgery. With a maximum clamping force of 29.6 N and a withdrawal force of 12.9 N, both values are significantly higher than those required in actual surgical procedures, ensuring stable operation under various complex conditions. In particular, the multi-degree-of-freedom design provides the electric needle holder with flexibility and adaptability that traditional needle holders cannot match, helping to shorten surgery time and improve suturing quality. Moreover, the electric needle holder demonstrated consistent withdrawal force when clamping different specifications of suturing needles, indicating high stability. This stability is crucial in clinical settings where various needle types are used, showcasing the broad applicability of the device. In practice, the instrument's versatility and adaptability will reduce the frequency of instrument changes, further enhancing overall surgical efficiency.

The experimental results show that the multi-degree-of-freedom electric needle holder can significantly improve suturing efficiency in complex surgical scenarios while maintaining operational stability and safety. Its performance in the pork suturing experiment confirms that the design goals—namely, enhancing suturing efficiency while ensuring the stability of the suture needle—have been achieved. Overall, the electric needle holder performs well, demonstrating clinical applicability, and has the potential to become an efficient tool for minimally invasive surgeries and complex suturing operations in the future.

For future clinical applications, further optimization of the grasper structure to increase friction with the suturing needle could enhance its adaptability and safety in various surgeries. Additionally, further research on the compatibility of the needle holder with other surgical instruments, such as scissors, could enable flexible multi-degree-of-freedom operation across a range of tools, improving surgical efficiency. Moreover, the integration of force sensors at the front of the instrument could allow for more precise control of the clamping force, enhancing the overall performance and safety of the device.

Conclusion

This paper presents the design of a multi-degree-of-freedom electric needle holder that can improve the efficiency of surgical training and operations while reducing surgeon fatigue. The needle holder uses a steel-wire pulley system that adapts to multi-angle operations in surgery, effectively reducing the frequency of angle adjustments and providing surgeons with flexible and stable support.

Experimental results validate the needle holder's performance: in clamping force tests, the device achieved a maximum clamping force of 29.6 N at 0°, with a minimum of 27.2 N, demonstrating the reliability and stability of the design. In withdrawal force tests, different specifications of suturing needles consistently achieved 12.9 N, showing that the device provides consistent holding ability for various needles and ensures operational safety. The pork suturing experiment demonstrated that the electric needle holder significantly reduced suturing time, improving efficiency by approximately 28% compared to the traditional needle holder. These results confirm that the design objectives have been met, demonstrating the device's wide clinical applicability and its potential to significantly improve surgical efficiency and accuracy in complex suturing scenarios, with considerable clinical value.

Author contributions: Lin Xin: Conceptualization, Methodology, Investigation, Formal analysis, Validation, Writing-Original Draft. Wenjie Yu: Control system design, Code implementation, Writing-Review&Editing. Yangzhi Liu: Experimental execution, Data curation. Liuxiao Cheng: Writing-Review&Editing, Visualization. Zhongxin Hu: Writing-Review&Editing, Resources. Chengli Song: Supervision, Project administration, Writing-Review&Editing (Corresponding Author).

References

[1] Ahmed I, Paraskeva P. A clinical review of single-incision laparoscopic surgery. Surgeon 2011;9(6):341-351.

[2] Rieder E, Martinec DV, Cassera MA, et al. A triangulating operating platform enhances bimanual performance and reduces surgical workload in single-incision laparoscopy. J Am Coll Surg 2011;212(3):378-384.

[3] Tang B, Hou S, Cuschieri SA. Ergonomics of and technologies for single-port lapaxroscopic surgery. Minim Invasive Ther Allied Technol 2012;21(1):46-54.

[4] Sato A, Hongo K, Sasaki T, et al. A novel needle holder for suturing in a deep and narrow surgical field: a technical note. J Neurosurg 2022;139(2):512-516.

[5] Dhumane PW, Diana M, Leroy J, et al. Minimally invasive single-site surgery for the digestive system: A technological review. J Minim Access Surg 2011;7(1):40-51.

[6] Kang SH, Won Y, Lee K, et al. Single-Incision Proximal Gastrectomy With Double-Flap Esophagogastrostomy Using Novel Laparoscopic Instruments. Surg Innov 2021;28(1):151-154.

[7] Jelinek F, Arkenbout EA, Henselmans PWJ, et al. Classification of Joints Used in Steerable Instruments for Minimally Invasive Surgery-A Review of the State of the Art. J Med Devices 2015;9(1):010801.

[8] Hu Y, Li W, Zhang L, et al. Designing, Prototyping, and Testing a Flexible Suturing Robot for Transanal Endoscopic Microsurgery. IEEE Rob Autom Lett 2019;4(2):1669-1675.

[9] Kim YJ, Cheng SB, Kim S, et al. A Stiffness-Adjustable Hyperredundant Manipulator Using a Variable Neutral-Line Mechanism for Minimally Invasive Surgery. IEEE Trans Rob 2014;30(2):382-395.

[10] Zheng Y, Wu BB, Chen YY, et al. Design and validation of cable-driven hyper-redundant manipulator with a closed-loop puller-follower controller. Mechatronics 2021;78:102605.

[11] Yoshiki N. Single-incision laparoscopic myomectomy: A review of the literature and available evidence. Gynecol Minim Invasive Ther 2016;5(2):54-63.

[12] 26th International Congress of the European Association for Endoscopic Surgery (EAES), London, United Kingdom, 30 May-1 June 2018: Poster Presentations. Surg Endosc 2018:483-614.

[13] Freschi C, Ferrari V, Melfi F, et al. Technical review of the da Vinci surgical telemanipulator. Int J Med Robot 2013;9(4):396-406.

[14] Kommu SS, Rané A. Devices for laparoendoscopic single-site surgery in urology. Expert Rev Med Devices 2009;6(1):95-103.

[15] Minor-Martinez A, Ordorica-Flores RM, Mota-Carmona JR, et al. Evaluating the performance of a new ergonomic laparoscopic needle holder for intracorporeal suturing. PLoS One 2025;20(1):e0313568.

[16] Faraj MK, Abed RI, Hamandi SJ, et al. Innovative surgical precision: The electronic pen needle holder based on neurophysiological principles. Surg Neurol Int 2024;15:264.

[17] Li JM, Wang SX, Wang XF, et al. Optimization of a novel mechanism for a minimally invasive surgery robot. Int J Med Robot 2010;6(1):83-90.

[18] Wang Z, Liu G, Qian S, et al. Tracking control with external force self-sensing ability based on position/force estimators and non-linear hysteresis compensation for a backdrivable cable-pulley-driven surgical robotic manipulator. Mech Mach Theory 2023;183:105259.

[19] Ramkumar SS, Rajanala R, Parameswaran S, et al. Experimental verification of failure of Amontons' law in polymeric textiles. J Appl Polym Sci 2004;91(6):3879-3885.

[20] Madhani AJ. Design of teleoperated surgical instruments for minimally invasive surgery. Massachusetts Institute of Technology 1998.

[21] Mucksavage P, Kerbl DC, Pick DL, et al. Differences in Grip Forces Among Various Robotic Instruments and da Vinci Surgical Platforms. J Endourol 2011;25(3):523-528.

[22] Bao X, Li W, Lu M, et al. Experiment study on puncture force between MIS suture needle and soft tissue. Biosurf Biotribol 2016;2(2):49-58.