nature portfolio

Peer Review File

Slipknot gauged mechanical transmission and robotic operation

Corresponding Author: Professor Tiefeng Li

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Attachments originally included by the reviewers as part of their assessment can be found at the end of this file.

Version 0:

Reviewer comments:

Referee #1

(Remarks to the Author)
The authors studied the slipknot as a means to control the force in suturing when tying knots.

I have several comments which I have listed as minor (typo, style) or major (potential concern, major bias) in the order wherein they appear in the manuscript.

1.General: this system only works for standing sutures which are very rarely used. Mostly anastomoses are either stapled or using a continuous (i.e. running) suture. Please discuss.(major)

2.General: is it possible that too much pressure is put on the side of the suture without the sliputure? (minor)

3.General: how to prevent a person, robot or other device to keep pulling after the sliputure has relaxed?(major)

4.General: can the sliputure sutures production already be standardised?(mnor)

5.Supplementary figure 9: are these differences also statistically significant?

Referee #4

(Remarks to the Author)
The paper presents a novel method for improving surgical suturing using slipknot-based mechanical transmission. By encoding force magnitude into slipknots, the researchers enable precise and consistent force application by limiting force while the slipknot is still active and a preset ceiling of tensile force. The additional visual feedback provides clinicians with feedback on this pseudo-tensile representation, acting more like a warning of high force. Their proposed "slipture" technique is an exciting concept that could potentially reduce the need for electronic force sensors in the tools. It is an extremely interesting solution to problems arising from the physical dissociation of surgeons and the surgical site.

The ex vivo and in vivo experiments demonstrate improved healing outcomes and reduced complications in surgical applications. The method has the potential for wide adoption in minimally invasive and laparoscopic surgeries as it requires no additional technology to integrate.

The paper is well-structured, with clear headings and a logical progression through both theoretical concepts and experimental validation. The manuscript gives a great overview for the general audience and adds detailed supplementary technical information on the manufacture and theory behind the knot theory, topology, and tribology. The figures and diagrams complement the text, aiding in the understanding of key concepts, results and applications.

Below I have some comments on the paper:

- The tensile tests that validate the force ranges focus on dry friction. While understandable due to the PTFE monofilament (allowing for comparison to the FE simulations), the paper does not mention the various fluids (potentially blood, peritoneal fluid, and saline) which could interact with the slipknot modify it's stage one force profile. This raises some questions about how accurately one could predict the force response in a real surgical environment, where fluids are abundant. Surgical environments introduce variables such as moisture, lubrication, and potentially biological interactions that could change the slipknot's performance regarding frictional behaviour and tensile force limits.
To solve this my main thought would be to include a comparative evaluation of the current tensile results alongside data on trials where a lubricant is applied to the knot and filament immediately prior to commencing the trial.

- Building on the previous point, the slipknot theory and contact model understandably assume a smooth-surfaced monofilament, but when translated to clinical materials (e.g., silk-braided sutures), do these assumptions still hold? Given that the model relies on the suture's elastic modulus and bending stiffness, one would expect braided sutures to exhibit different response magnitudes due to their inherently lower bending stiffness. This distinction, however, is not addressed in the current model. This then highlights a gap in the paper, as there is no explicit link between the behaviour of monofilaments in the tensile tests and the outcomes of the ex vivo and in vivo trials, which use Ethicon Silk sutures. Additional valuation of clinical sutures under tensile testing would keep consistency throughout.

- The paper highlights the potential for slipture in minimally invasive surgeries but falls short in addressing how it integrates with robotic surgical platforms. While the concept is promising for surgeons physically dissociated from the surgical site, a deeper discussion is needed on how slipknots could be adapted to work with the current generation of robotic systems, replacing the need for haptic and sensor-based feedback. Expanding on how slipknots could complement or replace these systems, particularly through visual force feedback, would greatly enhance the paper's relevance and applicability in robotic surgery.

- The paper dedicates most of its content to demonstrating the slipture technique's potential in surgical applications, which makes the concluding focus on its multiscale potential feel somewhat disconnected. While the multiscale possibilities are interesting, they diverge from the core narrative of the surgical focus, concluding in a less cohesive. To improve this, I see two options:
1. The conclusion should better align with the main theme of the paper by emphasising how the multiscale applications build on the surgical findings. For instance, the authors could frame the multiscale potential as a natural extension of successful surgical applications, highlighting the practical clinical success first and then transitioning to the broader impacts of the technique across various scales. Additionally, expanding on how the surgical outcomes demonstrate the robustness and versatility of the slipknot mechanism could provide a smoother transition to discussing its multiscale applicability.
2. Presenting the surgical results as a proof-of-concept could contextualise the technique's broader potential more effectively. Framing the paper as a focus on the general applications of the slipknot technique would be possible. However, multiple applications would need to be explored at a depth similar to that of surgery in order to feel balanced.

Minor Comments:

- Please clarify whether monofilament or braided sutures were used in the knot-tying force tests involving junior and senior surgeons.

- While the visual feedback mechanism for minimally invasive surgery is promising, it would be helpful to include more detail on how this can be practically implemented in surgery with the high likelihood of occlusions from blood, etc.

- The paper briefly mentions the stability of the slipknot over time (up to 32 days). Expand the reasoning for this and its relevance, especially for long-term suture reliability for surgery, given that the sliptures must be pre-tied to a specific force.

- The results for the knotting force in senior surgeons are missing. Adding this and statistical evidence is needed to back up the claim that the junior surgeons can surpass the senior.

- The comparison between junior and senior surgeons' performance with sliptures could be expanded slightly, explaining how this translates into clinical practice. For example, would you expect these to be replacements or as a training tool, as the data seems that senior surgeons have learned comparable accuracy without the sliptures' visual cue, similar to force applications in robotic surgery with./without haptics. My assumption is based on just looking at the graph; the stat analysis from the previous point will be necessary.

- A brief comment on the cost-effectiveness of the slipture, especially compared to electronic force-sensing alternatives, would further highlight its benefits for surgery

Referee #5

(Remarks to the Author)
The article notes a feature of the common slipknot that it acts as a mechanical force limiter in the transmission of force between the free ends of the line. An interesting application of this feature to the tying of sutures in surgical operations is studied in detail, with reasonable experimental evidence of the quality and repeatability of the force-limiting behavior and the effects of improved force regulation during suture tying on some outcomes such as post-surgical tissue blood supply, complication rates, and healing rates.

The paper really addresses three conceptually separate contributions; first, the idea of the "slipknot" as an implementation of a force-limiting mechanical structure; second, the application of that concept to surgery; and third, to provide evidence that regulation of the force during suture tying results in superior surgical outcomes. While the paper is interesting, it is not clear that all three of these contributions are fully explored yet.

The first contribution is interesting. The idea that a peak force will occur when opening the slipknot is self-evident. The part which is not self-evident is that the peak force can be reliably programmed. Relatively good agreement is shown between models and experiment, and the strong but simple relationship between Fpreset and Fpeak is a useful observation. The experimental validation provides some basis to trust the analysis conducted using the models. However, it would appear that friction, plasticity, and other complicated physical phenomena can affect the force required to open the knot. Presumably, in other materials, effects such as cohesion could play a role. Other than the initial tying force, the paper does not provide experimental evidence to validate the model-based understanding of the role of these other physical phenomena in producing precise peak forces. The choice to explore the effects of the time after setting (Fig. 2h) and speed of pulling the knot (Fig 2i) seems odd since no physical phenomena were hypothesized by which these variables should play a role. It is in particular odd that the conclusion is that the slipknot can reliably gauge operations without influence from the working environment. Is this true if the slipknot is characterized in a dry environment and then used in a wet one? Supplementary Fig. 20 seems to cast doubt on this since the friction parameter f2 has a significant impact on the force Fopen. Lastly, it is not clear what the DNA simulation is supposed to convey. The literature already contains plenty of references to slipknots in DNA. As already stated, the fact that the knot would require a peak force to open and that this force will depend on how tightly the knot is tied is relatively straightforward, so it is not clear to me what the need is for "validation" spanning geometric scales. This line of reasoning does not make the paper more "scientifically valid" and doesn't seem to serve a clear purpose in the context of the rest of the paper.

The second contribution is also an interesting one. However, if the paper's aim were only to solve this "engineering" problem of limiting suture tension, then other potential solutions might be competitive, limiting the significance of this contribution. Sacrificial mechanical features/components to serve force- or torque-limiting design functions have been a common strategy for a long time (e.g., the common shear pin). Other obvious strategies would be to produce sutures that break at the desired tension or to grasp the suture with a tool with a controlled gripping force on the suture. Perhaps there is something superior about the slipknot as a solution, but since no other solutions are even qualitatively explored or discussed, the paper leaves the feeling that the paper might be presenting a novel solution to the problem for the sake of its novelty alone rather than its advantages. With that said, the strategy does appear to work.

The third contribution seems well supported by the evidence, but readers may naturally wonder if there are reasons why sutures are not currently tied with explicit tension measurement or regulation. The obvious and unaddressed question in the paper is whether the "feasible" range of tensions can be predicted reliably a priori. One presumes that the "feasible range" would need to be established carefully in human studies and that it may depend not only on the specific surgical procedure but possibly other patient-specific factors. The paper does not discuss this practical challenge to application. One item not addressed by the paper is the type of knot that is being tied. Many different knots have been written about for surgical applications (see, e.g., [A], although the use of the term "slipknot" in that work refers to a knot which slides rather than slips open topologically). The strategy here seems to apply in only some circumstances, and it would be good if the paper were clearer about the scenarios in which the proposed solution would apply or not apply. Additionally, some important information about some of the experiments is missing. In the description of the methods for the comparison of anastomotic leakage, postsurgical adhesion, and tissue ischemia, it is not clear who performed the trials not involving the sliputure (i.e., relationship to the authors, level of experience, whether the surgeon tying the common sutures was blinded to the purpose of the study, etc.).

The discussion section of the paper has several weaknesses, in my opinion. The phrase "controlling force" is used haphazardly. The slipknot does not regulate the force; it can limit the force, but not control it in the technical sense (at least in the sense of the typical goals of standard control theory). Furthermore, the idea that designs can be enriched by incorporating tension and twist is a hypothesis even though it is stated as a fact. The same could be said of the link between precise and rapid mass production and the range of applications. It is also unclear how a slipknot would be applied in the context of body-sized humanoid robot movements since the knots can only be opened once. In general, the discussion is written in such a way that it claims more than it should, in my opinion, based on the evidence provided in the rest of the paper.

Ultimately, the work seems to mostly be of good technical quality, but the conclusions are not fully convincing because of some of the shortcomings noted above.

References

[A] Shimi, S. M, et al., "Comparative study of the holding strength of slipknots using absorbable and nonabsorbable ligature materials", Surg Endosc, 1994, vol 8., pp. 1285-1291.

Version 1:

Reviewer comments:

Referee #1

(Remarks to the Author)
No further comments, thank you for your answers.

Referee #4

(Remarks to the Author)
The paper presents an updated manuscript focused on the use of slipknot-based mechanical limits in sutures. The "sliptures" are evaluated in a variety pof surgical scenarios (benchtop tests, phantom suturing, live animal models) inticating their potetnial for use as a low-cost force limiter in surgery.

The authors have made significant changes in response to previous reviewer comments, including the addition of several new experiments. These new experiments are rigorous and directly address the prior round of reviewer concerns. The work remains relevant and timely, and the updates strengthen the paper considerably.

The revisions have clearly improved the overall quality of the work. The expanded mechanical testing, including experiments across different suture materials and anatomical lubricants, helps solidify the clinical use case. The investigation into plasticity effects also adds valuable detail about real-world mechanical behavior. Clinically, the inclusion of a comparative table evaluating different force-limiting devices provides additional context for the role sliptures might play. The new anatomical testing (particularly regarding the florescence and pressure evaluations) and the implementation of the autonomous braking system are both well-integrated and useful additions that enhance the manuscript’s relevance to surgical practice.

I see no further issues that remain after the previous review round. The manuscript now reads clearly and is well-supported by experimental data and visualizations.

Referee #5

(Remarks to the Author)
This paper presents a strategy for limiting the tensile forces applied during suture tying based on the inclusion of a slipknot in the suture thread, which ``slips out'' at a preset tensile force. Applicable to robotic surgery, manual laparoscopic techniques, and open surgery, this approach addresses the need for repeatable force application when pulling on the suture thread to tie the surgical knots. Although it is nearly self-evident that there will exist a peak force during the opening of the slipknot, it is perhaps surprising that this force can be programmed reliably into the knot. This is a simple but compelling example of ``intelligent'' behavior that results from purely mechanical action, without the need for electronic measurement and feedback control. As noted by the authors, many robotic surgery systems do not have the necessary functionality to sense the forces due to the additional design complexity, expense, and technical challenges of including them. The mechanics of the knot are clearly explained, and experimental data at multiple size scales soundly supports the technical conclusions. The approach is clever, low-cost, and initial experience reported here in both a human subjects experiment and an animal trial indicates that the sliputure technique may be a valuable operative technique once it is validated for specific surgical procedures. Since the opening of the slipknot can be detected visually, it is a promising technique for limiting force application during suturing in partially or fully automated surgical robotic systems.

The revisions have focused the article better on the core contribution of the work. The supplementary materials better explain the role of material plasticity in the mechanics and provide critical evidence about the reliability of the approach under varying environmental conditions (wet, dry, oiled, and over differences in the filament medium). Interestingly, direct tests clearly demonstrate that the performance is acceptable even when conditions vary from dry to saturated with simulated body fluids. Some models are now also provided to help understand the feasible force range, although it still seems likely that some amount of calibration for specific procedures will be needed in practice--which should be a solvable problem.

Referee #1:

The authors studied the slipknot as a means to control the force in suturing when tying knots.

I have several comments which I have listed as minor (typo, style) or major (potential concern, major bias) in the order wherein they appear in the manuscript.

1.General: this system only works for standing sutures which are very rarely used. Mostly anastomoses are either stapled or using a continuous (i.e. running) suture. Please discuss. (major)

Response: Thanks for your comment. Sliputure is applicable to continuous sutures, as demonstrated in our protocol. Detailed experimental procedures and discussions are presented below:

Stapled procedures and continuous sutures are indeed commonly used in tissue anastomosis. We have noticed some drawbacks of the staplers and continuous sutures that might be solved by our strategy. Staplers are available in various lengths and heights, but the size is fixed once selected, which may not accommodate individual anatomical characteristics, potentially causing excessive tension, tissue ischemia, and the need for additional sutures to ensure sealing[1]. Continuous sutures show comparable outcomes to standing sutures, but their reliance on the final stitch may impair blood supply[2,3]. Continuous sutures alone are unsuitable for certain procedures that require precise knot tension such as corneal repair[4], or involve delicate structures such as bilioenteric anastomosis of skinny bile ducts, where standing sutures are necessary to reduce the risk of luminal stricture and biliary leakage[5,6]. As a result, standing sutures provide comparably low leakage rates, and remain one of the most widely adopted surgical techniques[7,8].

Additionally, we studied the effects of tissue repair by continuous sutures, staplers, and sliputures. We have constructed acute colonic perforation with peritonitis models on Bama miniature pigs and performed colonic repair using the Da Vinci Xi robotic system. After repairing by sliputures, the colonic tissue showed flatness with few tissue tearing conditions and better instantaneous blood supply, highlighting the advantages of sliputures in limiting force during suturing (**Fig. R1**). The results have been added in **Discussion** (Page 11, Line 227-229): "Standing sutures with sliputures yield flat tissue appearance with adequate blood supply comparing with traditional stapled procedures and continuous sutures (**Supplementary Fig. 16**)." The experimental details have been included in **Methods** and **Supplementary Materials**.

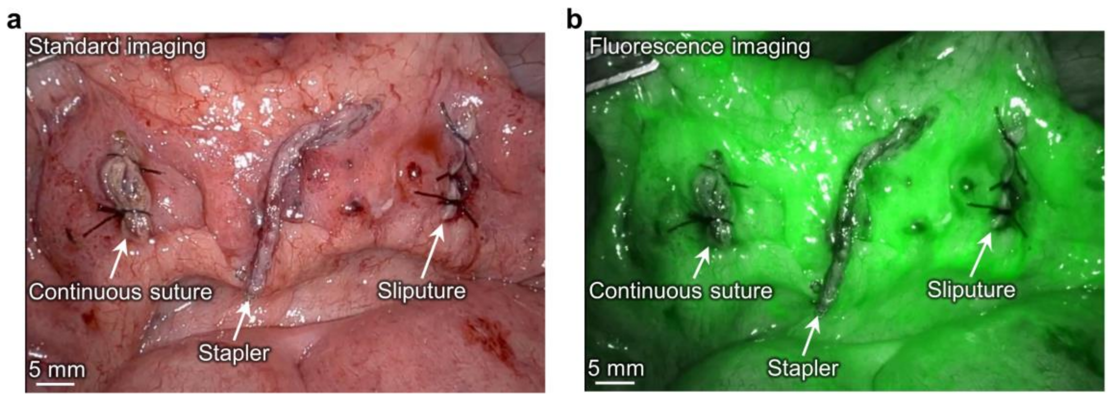

Fig. R1 (added in revised Supplementary Materials as Supplementary Fig. 16): The images of live porcine colonic repair by continuous suture, stapler, and sliputure under robotic system. a, Tissue appearance under standard imaging. **b,** Tissue appearance under fluorescence imaging 60 s post-injection of indocyanine green. Scale bars, 5 mm.

The repaired tissue appearance and blood supply results attribute to the pressure distribution. We have discovered an increasing pressure trend in conventional continuous sutures (**Fig. R2a**). The pressure follows a contact model (**Fig. R2b**), which we have included in **Supplementary Materials**:

Suture-tissue contact model

The appearance of the repaired tissue and its blood supply are attributed to the pressure distribution. A monotonic increase in contact pressure in conventional continuous sutures was observed (**Supplementary Fig. 28a**). Here we develop a model to analyse the distribution of the contact pressure between the suture and the tissue, as shown in **Supplementary Fig. 28b**. Let R represent the radius of the tissue, p_0 the preload caused by the tissue deformation, θ the angle swept by turns of the suture measured in radians. Governing equations for the tension in the suture, T, and the internal pressure between the suture and the tissue p, are listed as follows:

$$p(\theta)R = T(\theta) + p_0 R, T'(\theta) = \mu p(\theta) R, T(0) = T_0, \quad (S32)$$

and the solutions are

$$p(\theta) = e^{\mu\theta}\left(p_0 + \frac{T_0}{R}\right), T(\theta) = e^{\mu\theta} T_0 + e^{\mu\theta} p_0 R - p_0 R, \quad (S33)$$

from which an exponential relationship among p, T, and θ can be observed. This model predicts that the contact pressure p increases with θ, a trend that has been verified with the extracted pressure data (**Supplementary Fig. 28c**).

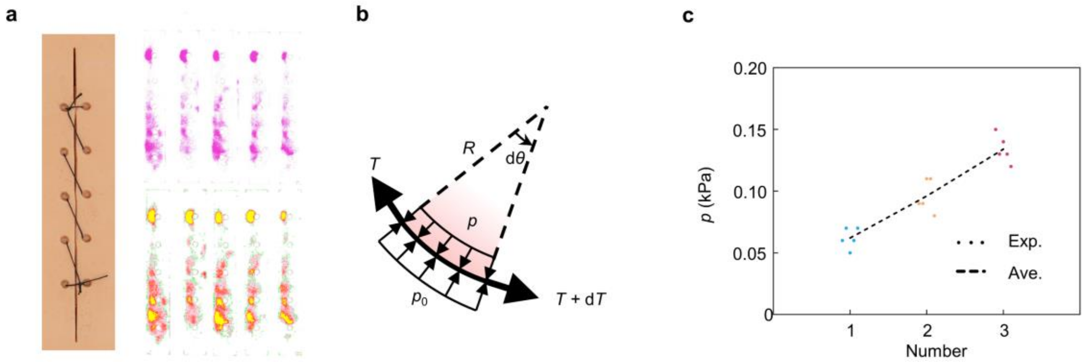

Fig. R2 (added in revised Supplementary Materials as Supplementary Fig. 28): Incision pressure measurement for continuous sutures of 5 stitches. a, The pressure distribution of a wound closed by continuous sutures. **b,** The scheme of the incision pressure analysis model. **c,** Quantified incision pressure for the middle 3 stitches extracted from the films.

Your valuable comments inspired us to integrate sliputures into continuous sutures. We have successfully demonstrated continuous 5 stitches with sliputure as follows (**Fig. R3**): a sliputure (Suture A) is used to place the first stitch to tie an anchor knot at the proximal end of the incision. Continuous sutures of 4 stitches are then performed using the left suture as usual[9], leaving the final stitch unknotted. Subsequently, a second sliputure with two slipknots (Suture B) is used to place the stitch at the distal end of the incision, with the slipknot near the incision being first used to form an anchor knot. Finally, Suture A and Suture B (one slipknot remained) are tied together to complete the final knot. We have added the discussion about sliputures for continuous sutures in **Results** (Page 11, Line 230-231): "The sliputure is also compatible with continuous sutures potentially (**Supplementary Fig. 17**), extending its applicability across diverse surgical scenarios." The experimental details have been included in **Methods** and **Supplementary Materials**.

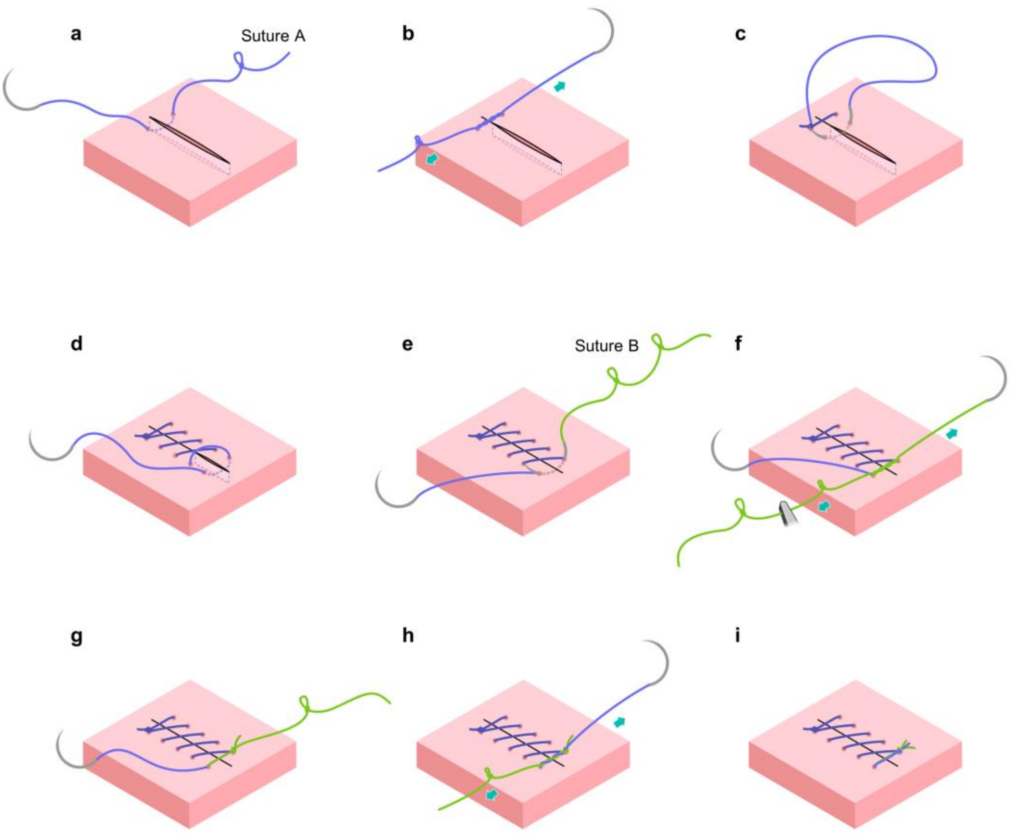

Fig. R3 (added in revised Supplementary Materials as Supplementary Fig. 17): Sliputures for continuous sutures protocol. a, Use a sliputure (Suture A) to place the first stitch..., **g, h,** Tie Suture A and Suture B (remains one slipknot) together to complete the final knot. **i,** Finished continuous sutures with sliputures.

2.General: is it possible that too much pressure is put on the side of the suture without the sliputure? (minor)

Response: The surgeon does not exert excessive force or pressure on the side of the suture without the slipknot, as confirmed by both theoretical predictions and experimental results.

We have conducted experiments to measure and compare the forces on both sides of sliputures. The side with the slipknot was pulled and defined as the active side, whereas the other side without the slipknot was held stationary and defined as the fixed side. We found that the force on the fixed side was consistently lower than that on the active side. This behavior also follows the model in the previous comment response, giving that:

$$\frac{p_{\text{fixed}}}{p_{\text{active}}} = e^{-\mu\pi} \approx \frac{T_{\text{fixed}}}{T_{\text{active}}} < 1.$$

For the tested friction coefficient between the suture and the silicone practice model, μ = 0.283 ± 0.003, we obtain $T_{\text{fixed}}/T_{\text{active}}$ = 0.411, which aligns well with experimental observations ($T_{\text{fixed}}/T_{\text{active}}$ = 0.420 ± 0.176) (**Fig. R4**). We have added the model in **Supplementary Materials**:

Suture-tissue contact model

This model also provides a quantitative link between the two sides of the sliputure. The side with the slipknot was pulled and defined as the active side, whereas the other side without the slipknot was held stationary and defined as the fixed side. From Eq. (S33) we have

$$\frac{p_{\text{fixed}}}{p_{\text{active}}} = e^{-\mu\pi} \approx \frac{T_{\text{fixed}}}{T_{\text{active}}} < 1, \tag{S34}$$

which predicts that the force on the fixed side will be consistently lower than that on the active side. For the tested friction coefficient between the suture and the silicone practice model, $\mu = 0.283 \pm 0.003$, we obtain $T_{\text{fixed}}/T_{\text{active}} = 0.411$, which aligns well with experimental observations ($T_{\text{fixed}}/T_{\text{active}} = 0.420 \pm 0.176$) (**Supplementary Fig. 29**)

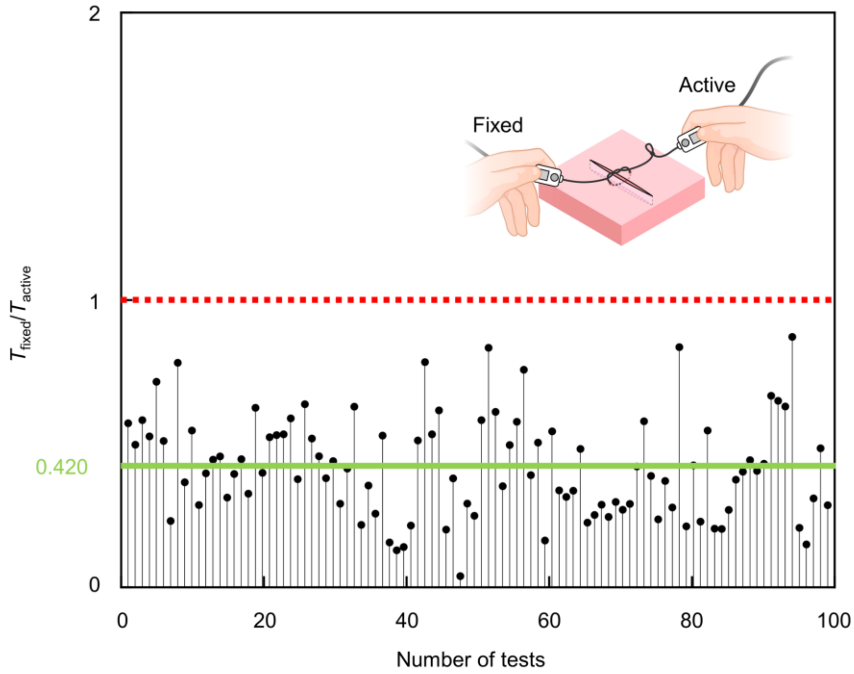

Fig. R4 (added in revised Supplementary Materials as Supplementary Fig. 29): Experimental ratio of T_{fixed} to T_{active} across 100 tests.

3.General: how to prevent a person, robot or other device to keep pulling after the sliputure has relaxed? (major)

Response: Human reaction time is sufficient to stop pulling before the buffer zone of the sliputure is exhausted, thereby preventing over-pulling. For robotic systems, a vision-based automatic braking module has been developed, which identifies the opened slipknot and autonomously halting the pulling action. Detailed experimental validation and discussions are provided below.

When the sliputure is relaxed, the released length of the sliputure guarantees a buffer zone (**Fig. R5**). This buffer zone provides both visual and force cues that assist in preventing over-pulling. We demonstrate stop pulling after slipknot opening in both manual operations by surgeons and procedures conducted using the Da Vinci Xi robotic system.

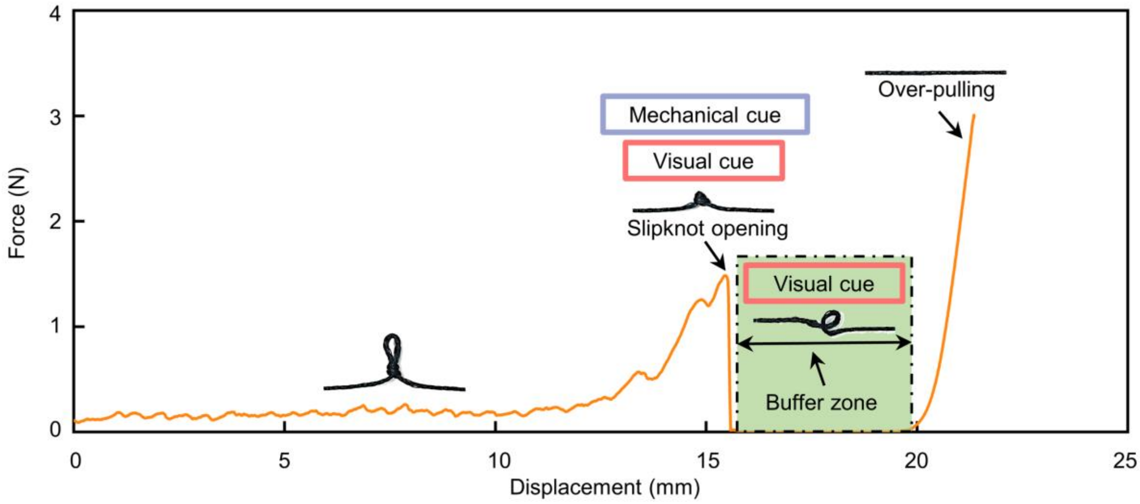

Fig. R5 (added in revised Supplementary Materials as Supplementary Fig. 30): Force-displacement curve of sliputure. When the slipknot is opened, a redundant length of sliputure is deployed, forming a "buffer zone" where the loading force remains null. This configuration provides both mechanical and visual cues.

For human testing, 10 surgeons were recruited to perform knot tying using sliputures on silicone practice models (**Fig. R6**). Based on video recordings and corresponding force-time curves, it was confirmed that in all 50 tests, surgeons were able to recognize the opened slipknot and stop pulling before the buffer zone was exhausted (**Fig. R7**).

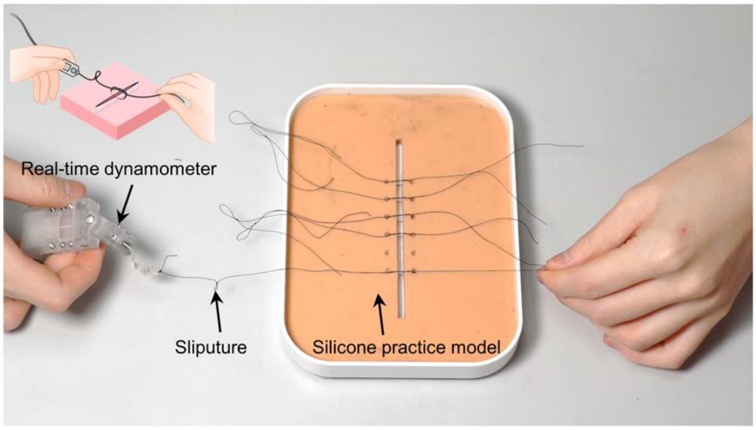

Fig. R6: Schematic and conceptual illustration of sliputures over-pulling test.

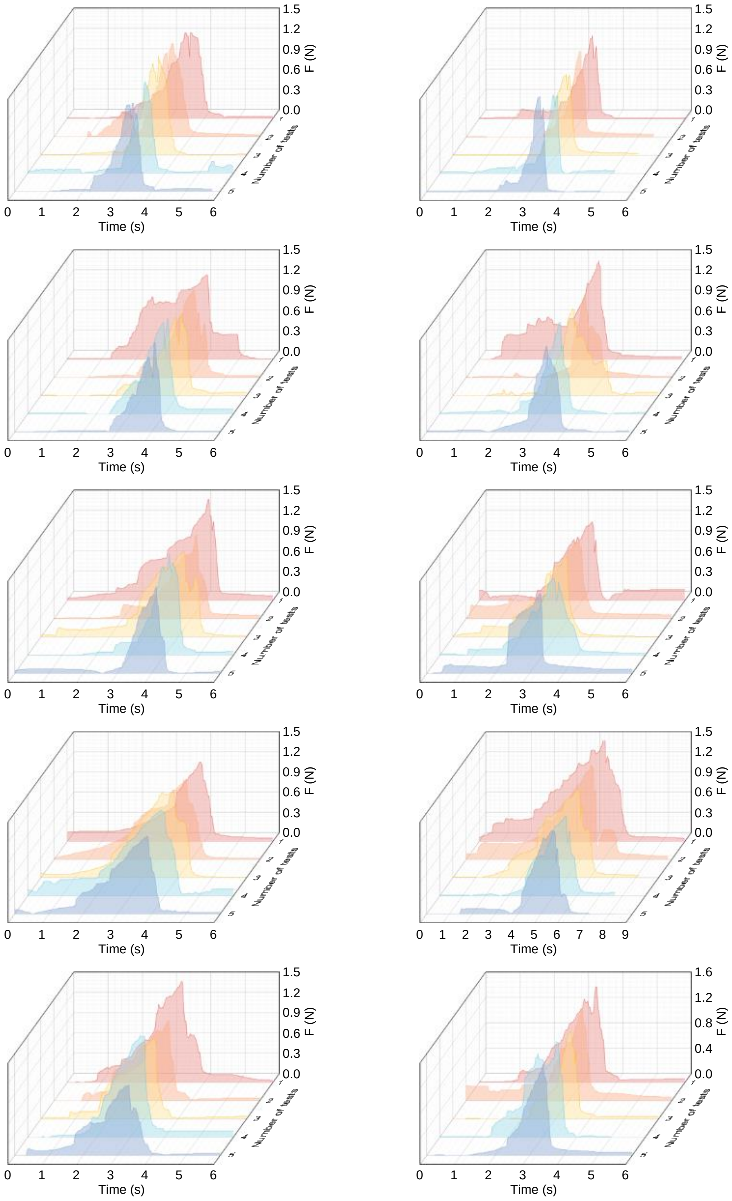

Fig. R7: Force-time curves for sliputures over-pulling test performed by surgeons under open set. The force-time curves showed that the force was rapidly released after F_{peak}, indicating that no over-pulling occurred during the procedure.

For robotic testing, 10 surgeons were recruited to perform knot tying using the Da Vinci Xi robotic system (**Fig. R8**). Each surgeon completed 10 tests with common sutures and another 10 with sliputures on silicone practice models placed in a training box. In all tests involving sliputures, surgeons successfully recognized the opened slipknot and stopped pulling before the buffer zone was exhausted. Additionally, the average knotting velocity was recorded as 1.614 ± 1.154 mm/s for common sutures and 1.919 ± 1.107 mm/s for sliputure. Given that the buffer zone with 4.379 ± 0.263 mm (F_{tying} = 0.35 N), the surgeons had more than 1.360 seconds to react.

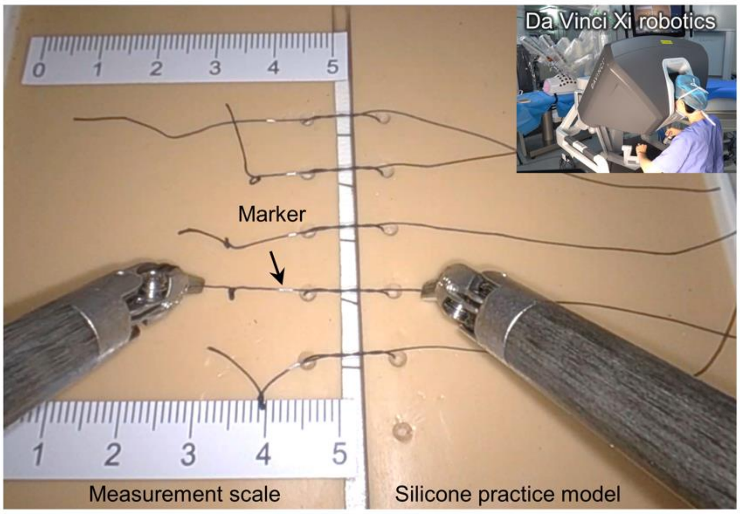

Fig. R8: Sliputures over-pulling test performed under robotic set. Surgeons performed tests with sliputures on a silicone practice model equipped with markers and a measurement scale using the Da Vinci Xi robotic system. Markers and the measurement scale enable precise tracking of instrument tip movement velocity.

Furthermore, we have developed a vision-based automatic-braking module in the robots to effectively prevent over-pulling of the sliputure automatically. This system enabled robotic arms to terminate the pulling motion by tracking the opened slipknot of the sliputure. Intuitive Surgical provides a customized Da Vinci Xi robotic system, enabling direct control via a local workstation (Ubuntu 22.04, Intel Core i9-14900, NVIDIA RTX 4090m). RGB images captured from a robotic first-person view were converted into a grey image. We implemented template matching using the Scale-Invariant Feature Transform (SIFT) operator from OpenCV, achieving a real-time processing speed of over 30 FPS. When a slipknot opening is detected (i.e. a grey image is matched with one of the template within the knot template set), a stop signal will be sent to the robot instantly, and the robotic instrument halts within 0.062 mm of movement, which is substantially shorter than the typical buffer zone. As illustrated in **Fig. R9** and **Fig. R10**, a red stop marker is displayed when the opening of the slipknot is detected, and the robotic instrument halts automatically. The effectiveness of the system was validated in live porcine colonic repair, demonstrating its clinical applicability.

We have added the robotic automatic-braking function in **Results** (Page 11, Line 230 to Page 12 Line 241): "The sliputure is designed to work with the current robotic systems, which is not equipped with dedicated force sensors. We integrated a vision-based automatic-braking module into a customized Da Vinci Xi robotic system…, visual force feedback and significantly enhancing sliputures' applicability in robotic surgery (**Fig. 4d, e**, **Supplementary Fig. 18, Video 11, 12**)." Detailed information has been included in **Methods** and **Supplementary Materials**.

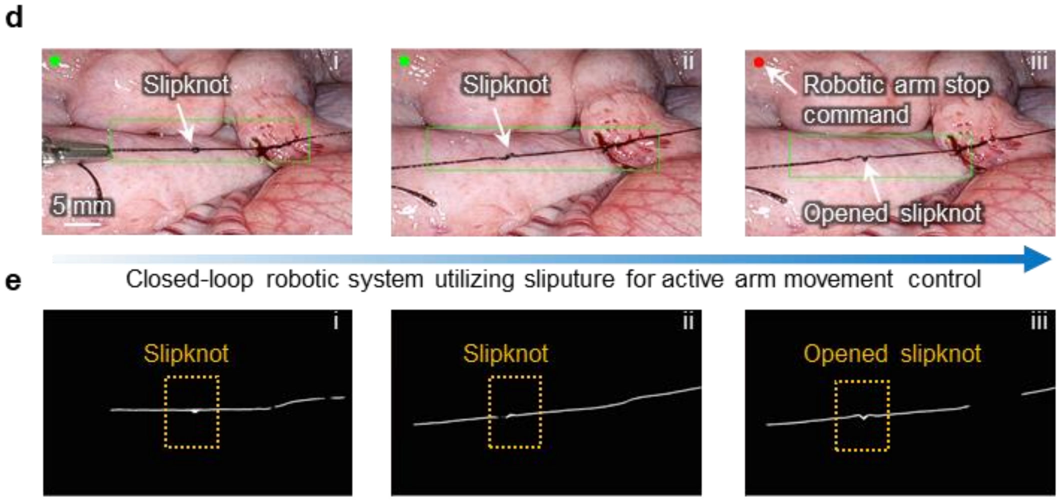

Fig. R9 (added in revised Manuscript as Fig. 4d, e): Slipknot gauges the intelligent operation of robots. d, Validation of the vision-based automatic-braking experiment in an *in vivo* porcine model. Real-time image processing for slipknot detection. Upon slipknot open, a stop command was activated to terminate the robotic movement. Scale bar, 5 mm. **e,** The slipknot was recognized from the RGB images and converted into real-time grey images. The slipknot opening was detected by matching the images to opened slipknot configuration.

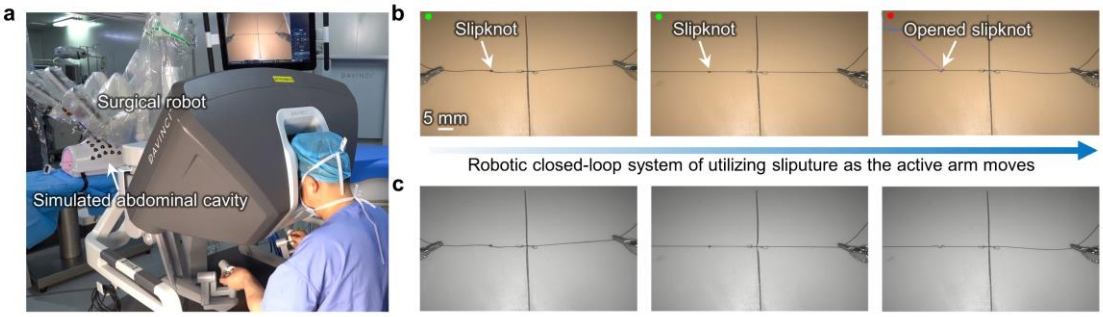

Fig. R10 (added in revised Supplementary Materials as Supplementary Fig. 18): Validation of the vision-based automatic-braking experiment in the silicone practice model. a, The surgeon employs sliputures to repair the silicone practice model using the Da Vinci robotic system under real-time monitoring. **b, c,** The system-triggered red stop marker was activated upon slipknot opening as the active arm moves on the silicone practice model.

4. General: can the sliputure sutures production already be standardized? (minor)

Response:
The production of sliputure sutures has been standardized. The detailed experimental procedures are as follows:
In the initial submission, all slipknots used in our tests were constructed with the wire-wrapping board depicted in **Supplementary Fig. 1**, ensuring the intended spatial

structure. The slipknots were subsequently tightened using a Zwick/Roell Z10/Z20 tensile testing machine equipped with an Xforce HP load cell (capacity: 200 N), enabling precise application of the F_{tying}. Despite the manual nature of this process, the sliputures demonstrated a high consistency of 95.4%.

We sincerely appreciate the comment highlighting the importance of standardized and scalable sliputure fabrication. We have developed an automatic slipknot fabrication machine for the standardized fabrication of sliputures (**Fig. R11**, **Video 14**). This system allowed regulation of the knot loops of sliputures (from single to multiple) and accurate adjustment of F_{tying} from 0.1 N to 10 N.

We have added the standardized fabrication of sliputures in **Discussion** (Page 13, Line 258-260): "An automatic slipknot fabrication machine enables standardized and on-demand production, supporting scalable application (**Supplementary Fig. 21, Video 14**)."

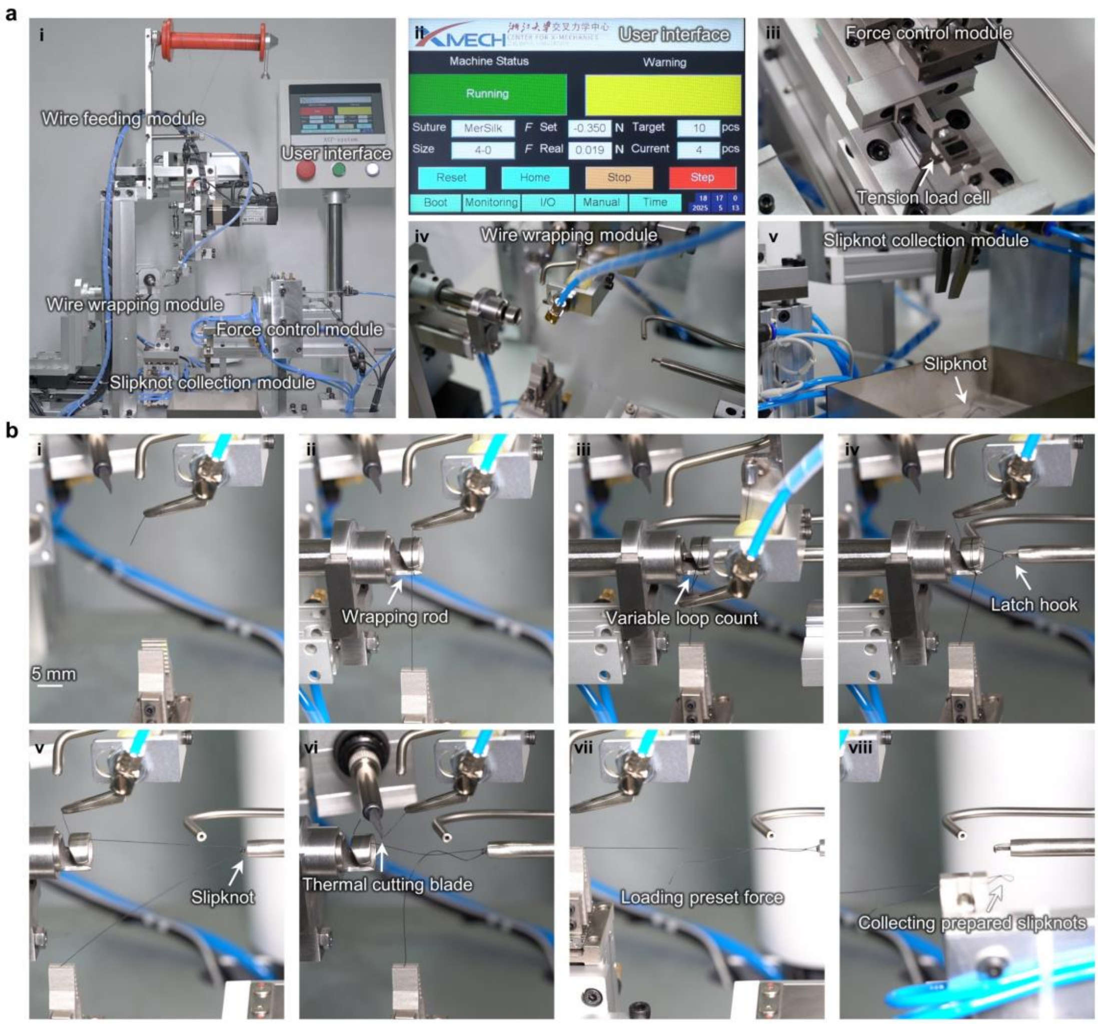

Fig. R11 (added in revised Supplementary Materials as Supplementary Fig. 21): Automatic slipknot fabrication machine. a, (i) Overall view of the system, which integrates modules of wire feeding, force control, wire wrapping, slipknot collection, and a user interface…, **(viii)** After securing the suture with the pneumatic gripper at a defined location, the latch hook releases, and a pneumatic device ejects the slipknot into storage. This automated cycle repeats continuously, facilitating high-throughput, standardized slipknot production from bulk suture materials.

5.Supplementary figure 9: are these differences also statistically significant?

Response: We have conducted a Fisher's exact test for surgery-related complications between sliputure and common suture group. There was no significant difference of macroscopic colonic leaks (P = 0.474), while there was a significant difference of postsurgical adhesions (P = 0.003) between two groups. And we have added the content in **Results** (Page 9, Line 180-184): "Regarding surgery-related complications, sliputure-treated animals show no macroscopic colonic leaks compared to common suture-treated animals (0/10 leak *vs.* 2/10 leak, P = 0.474), and fewer postsurgical adhesions appeared after using sliputures than common sutures (3/10 adhesions *vs.* 10/10 adhesions, P = 0.003) (**Supplementary Fig. 11**)."

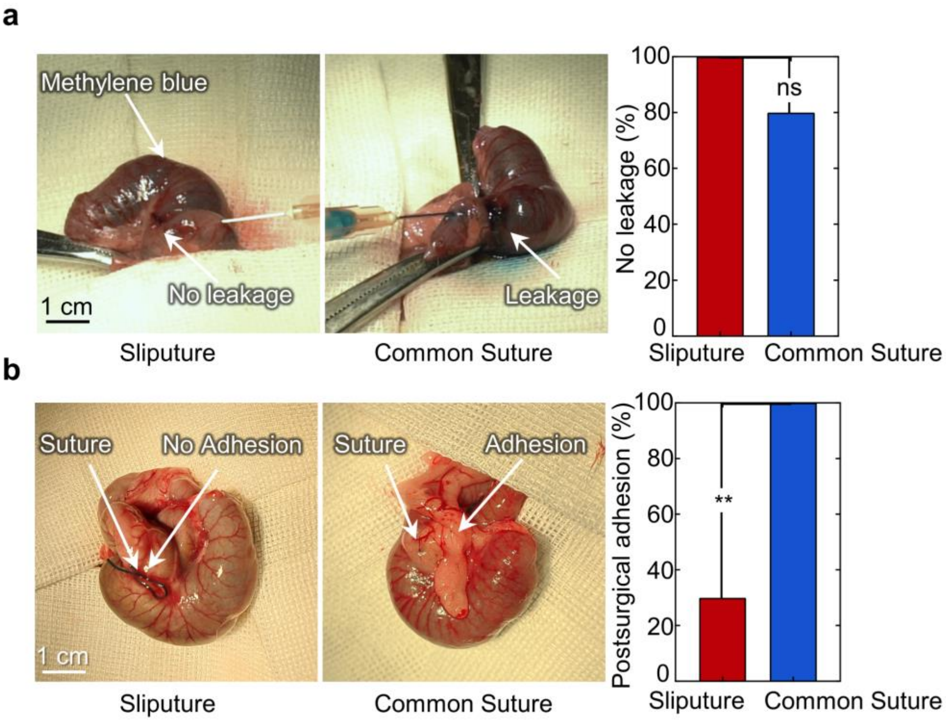

Fig. R12 (updated in revised Supplementary Materials as Supplementary Fig. 11): Comparison of the mechanical influence on surgery-related complications between sliputure and common suture. a, b, Comparison of the mechanical influence on leakage (**a**) and adhesion rates (**b**) after being repaired by sliputures and common sutures. ns, not significant; **, $P < 0.01$.

Referee #4 (Remarks to the Author):

The paper presents a novel method for improving surgical suturing using slipknot-based mechanical transmission. By encoding force magnitude into slipknots, the researchers enable precise and consistent force application by limiting force while the slipknot is still active and a preset ceiling of tensile force. The additional visual feedback provides clinicians with feedback on this pseudo-tensile representation, acting more like a warning of high force. Their proposed "slipture" technique is an exciting concept that could potentially reduce the need for electronic force sensors in the tools. It is an extremely interesting solution to problems arising from the physical dissociation of surgeons and the surgical site.

The ex vivo and in vivo experiments demonstrate improved healing outcomes and reduced complications in surgical applications. The method has the potential for wide adoption in minimally invasive and laparoscopic surgeries as it requires no additional technology to integrate.

The paper is well-structured, with clear headings and a logical progression through both theoretical concepts and experimental validation. The manuscript gives a great overview for the general audience and adds detailed supplementary technical information on the manufacture and theory behind the knot theory, topology, and tribology. The figures and diagrams complement the text, aiding in the understanding of key concepts, results and applications.

Below I have some comments on the paper:

- The tensile tests that validate the force ranges focus on dry friction. While understandable due to the PTFE monofilament (allowing for comparison to the FE simulations), the paper does not mention the various fluids (potentially blood, peritoneal fluid, and saline) which could interact with the slipknot modify it's stage one force profile. This raises some questions about how accurately one could predict the force response in a real surgical environment, where fluids are abundant. Surgical environments introduce variables such as moisture, lubrication, and potentially biological interactions that could change the slipknot's performance regarding frictional behaviour and tensile force limits.

To solve this my main thought would be to include a comparative evaluation of the current tensile results alongside data on trials where a lubricant is applied to the knot and filament immediately prior to commencing the trial.

Response: Thanks for your comments. We have conducted additional experiments characterizing the static friction of three filaments (PTFE monofilament, braided absorbable sutures (Vicryl), and braided non-absorbable sutures (Mersilk)) in four media (synthetic blood, simulated body fluid, natural saline, and silicone oil). All friction tests employed the apparatus described in **Fig. R13a**.

We have added the content in **Results** (Page 6, Line 119-122): "Slipknots of different materials and structures, when submerged in various liquid media, exhibit different friction coefficients (**Supplementary Fig. 5**). This variation subsequently affects F_{peak} aligning with the model prediction (**Supplementary Fig. 6**).”

We also have added a new section in **Supplementary Materials** as follows:

Opening sliputures under dry, moist, and lubricated conditions

Surgical environments introduce variables such as moisture and lubrication that could alter the slipknot’s performance regarding frictional behavior and tensile force limits. To understand this, we further studied the influence of friction in several filaments when they are in different working environments. Specifically, experiments characterizing the static friction of three filaments (PTFE monofilament, braided absorbable sutures (Vicryl), and braided non-absorbable sutures (Mersilk)) in four media (synthetic blood, simulated body fluid, natural saline, and silicone oil) were conducted. The frictional coefficient parameter μ was tested through the apparatus described in **Supplementary Fig. 5a**, and the parameter f_2 is derived from the corresponding tensile tests of the slipknot (**Supplementary Table 2-4**).

We measured the friction coefficient of the lines in various volumes of liquids (**Supplementary Fig. 5b-e**). The friction coefficients of PTFE fluorocarbon string and Vicryl exhibited little change (< 10%) in synthetic blood, simulated body fluid, and natural saline as compared to the dry condition. However, in silicone oil, the friction coefficients of PTFE decreased by 27.737%, and that of Vicryl increased by 14.805%, respectively. The friction coefficient of Mersilk was approximately 100% higher in synthetic blood, simulated body fluid, and natural saline than that in the dry condition, while it decreased by 17.853% in silicone oil.

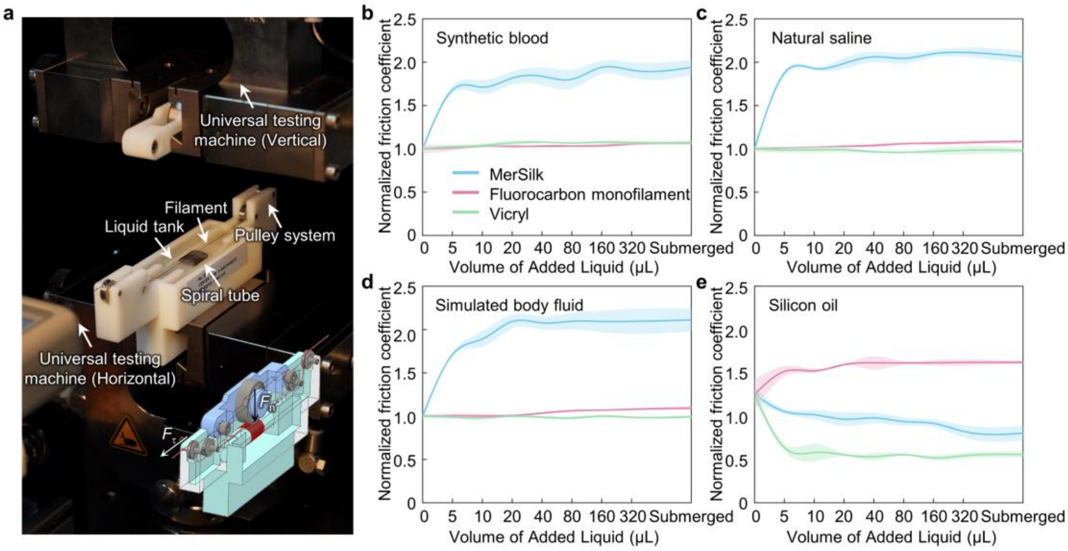

Fig. R13 (added in revised Supplementary Materials as Supplementary Fig. 5): Measurement of the friction coefficient of filaments in moist and lubricated conditions. a, The filament friction measurement setup in liquid environments. The pulley system allows the filament to be immersed in the tank with varying amounts of liquid. The testing machine (vertical) applies a normal force, F_n, pressing the filament firmly against a spiral tube wrapped with a single layer of the same filament. The testing machine (horizontal) pulls the single filament steadily, allowing the measurement of the tangential force, F_{τ}. **b-e,** Normalized friction coefficient of Mersilk, fluorocarbon monofilament, and Vicryl in various volumes of (**b**) synthetic blood, (**c**) natural saline, (**d**) simulated body fluid, and (**e**) silicone oil.

We next tested F_{peak} of the slipknots when they were submerged in different liquids and fabricated with various values of F_{tying} (**Supplementary Fig. 6**). F_{peak} of PTFE monofilament sliputures exhibited no measurable change in the three aqueous media (synthetic blood, simulated body fluid, natural saline), while a remarkable reduction in silicone oil; F_{peak} of Mersilk sliputures exhibited a slight increase in three aqueous media and some reduction in silicone oil; and F_{peak} of Vicryl sliputures increased in all four liquids, with the largest increment in silicone oil. We found that the theoretical model is applicable for predicting the peak force of slipknots fabricated from both monofilament filaments and braided sutures, and the results largely mirror the friction trends predicted by the analytical model (**Supplementary Table 5-8**), particularly in silicone oil, where the model accurately predicted the increase and decrease for all three filaments. However, for Mersilk in aqueous media, the theoretical outcome leads to a higher prediction increase compared to the actualyl measured increase. Such discrepancy is potentially due to the model not accounting for the effect of swelling on the radius of constraint, R, in Eq. (S30), which could overestimate the peak force.

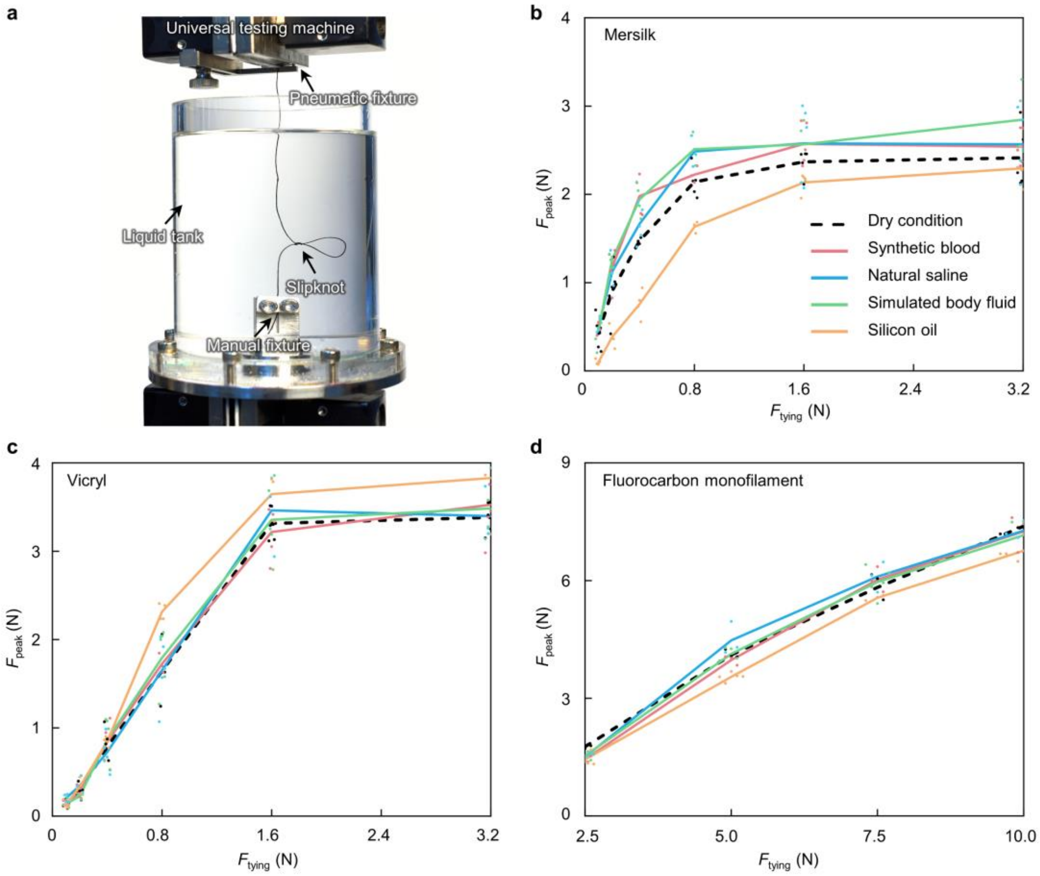

Fig. R14 (added in revised Supplementary Materials as Supplementary Fig. 6): Measurement of the relationship between F_{peak} and F_{tying} of sliputures in dry,

moist and lubricated conditions. a, The uniaxial stretching setup in liquid environments. The manual fixture at the bottom presses the sliputure into the groove and is screwed into the pre-threaded section in the liquid tank to ensure coaxiality during the tensile test. The upper and lower fixtures are brought as close as possible before starting the test to minimize the effect of buoyancy. **b,** The relationship between F_{peak} and F_{tying} for sliputure made with Mersilk in synthetic blood, natural saline, simulated body fluid, and silicone oil. **c,** The relationship between F_{peak} and F_{tying} for sliputure made with Vicryl in synthetic blood, natural saline, simulated body fluid, and silicone oil. **d,** The relationship between F_{peak} and F_{tying} for sliputure made with fluorocarbon monofilament in synthetic blood, natural saline, simulated body fluid, and silicone oil.

Table R1 (added in revised Supplementary Materials as Supplementary Table 2): Parameters of PTFE monofilament sliputures in silicone oil and dry condition.

Conditions	E (GPa)	d (mm)	μ	f_2 (F_{tying} = 2.500 N)	f_2 (F_{tying} = 5.000 N)	f_2 (F_{tying} = 7.500 N)	f_2 (F_{tying} = 10.000 N)
Dry	2.700	0.235	0.165	0.543	1.649	2.862	3.900
Silicone oil	2.700	0.235	0.119	0.547	1.380	2.666	3.393

Table R2 (added in revised Supplementary Materials as Supplementary Table 3): Parameters of Mersilk sliputures in silicone oil, synthetic blood, and dry condition.

Conditions	E (GPa)	d (mm)	μ	f_2 (F_{tying} = 0.400 N)	f_2 (F_{tying} = 0.800 N)	f_2 (F_{tying} = 1.600 N)	f_2 (F_{tying} = 3.200 N)
Dry	9.745	0.150	0.145	0.246	0.442	0.713	0.763
Silicone oil	9.745	0.150	0.119	0.065	0.233	0.374	0.548
Synthetic blood	9.745	0.150	0.260	0.328	0.622	1.104	1.125

Table R3 (added in revised Supplementary Materials as Supplementary Table 4): Parameters of Vicryl sliputures in silicone oil and dry condition.

Conditions	E (GPa)	d (mm)	μ	f_2 (F_{tying} = 1.600 N)	f_2 (F_{tying} = 3.200 N)
Dry	14.668	0.150	0.157	0.551	0.611
Silicone oil	14.668	0.150	0.180	0.521	0.591

Table R4 (added in revised Supplementary Materials as Supplementary Table 5): The comparison of F_{peak} of PTFE monofilament sliputures in silicone oil and dry condition.

F_{tying} (N)	Exp.- dry (N)	Exp.- liquid (N)	Theory-dry (N)	Theory-liquid (N)
2.500	1.766	1.439	1.970	1.646
5.000	4.104	3.548	3.371	2.655
7.500	5.826	5.563	4.864	4.179
10.000	7.388	6.763	6.115	5.026

Table R5 (added in revised Supplementary Materials as Supplementary Table 6): The comparison of F_{peak} of Mersilk sliputures in silicone oil and dry condition.

F_{tying} (N)	Exp.-dry (N)	Exp.-liquid (N)	Theory-dry (N)	Theory-liquid (N)
0.400	1.517	0.756	1.978	1.516
0.800	2.142	1.633	2.226	1.721
1.600	2.368	2.135	2.568	1.894
3.200	2.414	2.295	2.631	2.107

Table R6 (added in revised Supplementary Materials as Supplementary Table 7): The comparison of F_{peak} of Mersilk sliputures in synthetic blood and dry condition.

F_{tying} (N)	Exp.-dry (N)	Exp.-liquid (N)	Theory-dry (N)	Theory-liquid (N)
0.400	1.517	1.979	1.978	3.538
0.800	2.142	2.223	2.226	3.962
1.600	2.368	2.571	2.568	4.647
3.200	2.414	2.540	2.631	4.677

Table R7 (added in revised Supplementary Materials as Supplementary Table 8): The comparison of F_{peak} of Vicryl sliputures in silicone oil and dry condition.

F_{tying} (N)	Exp.- dry (N)	Exp.- liquid (N)	Theory-dry (N)	Theory-liquid (N)
1.600	3.316	3.647	3.391	3.733
3.200	3.383	3.829	3.468	3.826

- Building on the previous point, the slipknot theory and contact model understandably assume a smooth-surfaced monofilament, but when translated to clinical materials (e.g., silk-braided sutures), do these assumptions still hold? Given that the model relies on the suture's elastic modulus and bending stiffness, one would expect braided sutures to exhibit different response magnitudes due to their inherently lower bending stiffness. This distinction, however, is not addressed in the current model. This then highlights a gap in the paper, as there is no explicit link between the behaviour of monofilaments in the tensile tests and the outcomes of the ex vivo and in vivo trials, which use Ethicon Silk sutures. Additional valuation of clinical sutures under tensile testing would keep consistency throughout.

Response: Our assumptions remain valid when applied to clinical materials, such as Mersilk and Vicryl. Detailed theoretical analysis and experimental validation are provided below:

In the theory, we defined the filament with friction coefficient of μ, it contributes to the F_{peak}, following Eq. (S28) in Supplementary Materials:

$$F = F(g) = f_2 + g + \mu^2 g + \mu\sqrt{2f_2 g + g^2 + g^2\mu^2}, \tag{S28}$$

when translated to clinical materials including Mersilk and Vicryl, they have friction coefficients that can be tested by the method described in previous response. We substitute the friction coefficient in the model, and the F_{peak} prediction matched the experimental results (**Fig. R15**).

We additionally measured the effective Young's modulus and calculated the bending stiffness of the two widely used braided clinical sutures: Mersilk (non-absorbable) and Vicryl (absorbable). In the model, the bending stiffness appears as EI, where E is the effective (structure-averaged) Young's modulus and I is the second moment of area. For both monofilaments and braided sutures, we determine E directly from uniaxial tensile experiments. The fact that a braided construction complicates an exact diameter measurement does not propagate into the peak force calculation, since the diameter d cancels out in the elastic force term g_{max}, as described in the flowchart (**Fig. R16**).

Although the diameters 4-0 braided sutures are smaller than PTFE monofilament, their measured effective moduli are unexpectedly high—9.745 GPa for Mersilk and 14.668 GPa for Vicryl, the calculated bending stiffnesses are still high, in the same orders of magnitude to that of PTFE monofilament. As a result, the experimentally observed F_{peak} values for both braided sutures coincide with the model predictions.

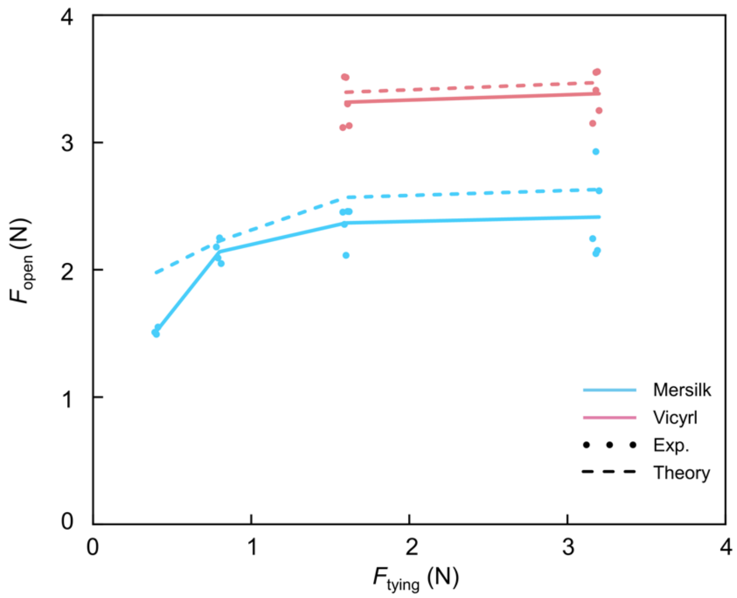

Fig. R15: Comparison of F_{peak} between experimental results (dots) and theoretical predictions (dashed lines) for Mersilk (blue) and Vicryl (red). Solid lines represent the mean experimental values for each suture.

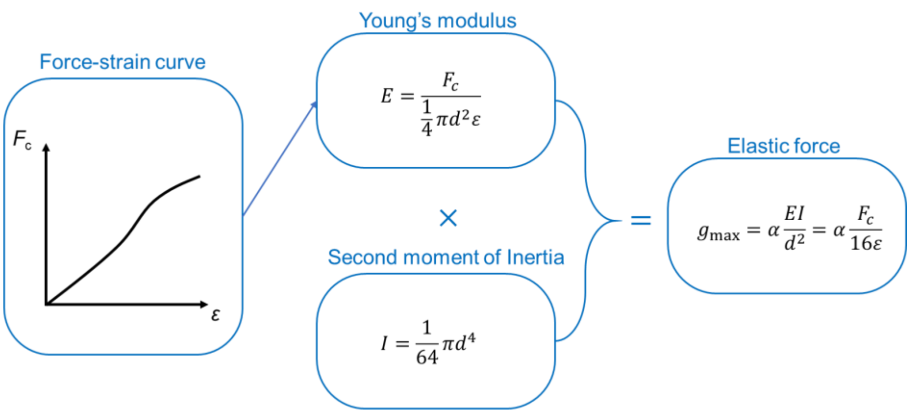

Fig. R16: Flowchart illustrating the calculation of the bending stiffness and elastic force. The effective Young's modulus is determined through uniaxial tensile tests, and the diameter d is eliminated in the elastic force.

- The paper highlights the potential for slipture in minimally invasive surgeries but falls short in addressing how it integrates with robotic surgical platforms. While the concept is promising for surgeons physically dissociated from the surgical site, a deeper discussion is needed on how slipknots could be adapted to work with the current generation of robotic systems, replacing the need for haptic and sensor-based feedback. Expanding on how slipknots could complement or replace these systems, particularly through visual force feedback, would greatly enhance the paper's relevance and applicability in robotic surgery.

Response: Thanks for your insightful comments. To further investigate the practicability and superiority of the sliputures, we have designed a pure vision-based surgical robot system framework using the Da Vinci Xi robotic system. Both silicone and live porcine experiments were conducted to verify the applicability of our proposed non-electronic sliputures with the vision-only approach in robotic surgery without sensors.

Specifically, firstly, we integrated a vision-based automatic-braking module into a customized Da Vinci Xi robotic system developed in collaboration with Intuitive Surgical, shown in **Fig. R17**, in which an additional sliputure detection branch (dashed line labelled with Number 2) was introduced to realize instant stop of the surgeon's pulling operation.

Secondly, to guarantee the real-time accuracy of sliputure detection (including slipknot detection), we proposed a lightweight neural network (named SlipknotNet) with 61.5 million parameters based on the U-Net structure, shown in **Fig. R18**. RGB images from the robot's endoscope are fed into SlipknotNet, which extract sliputures from the image and predict whether there exists an opened slipknot by knot template matching on extracted sliputures. SlipknotNet is trained using over 2,200 self-annotated images on a local workstation and can infer endoscope images at 30 FPS.

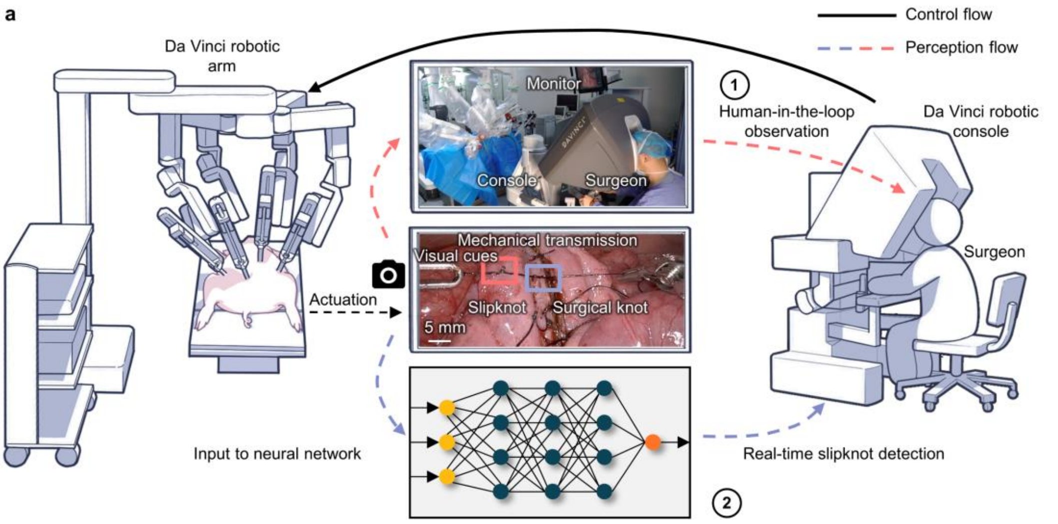

Fig. R17 (added in revised Manuscript as Fig. 4a): Slipknot gauges the intelligent operation of robots. a, The mechanical transmission route of applying sliputures in robotic surgery. The real-time imaging provides visual cues to humans and robots, enabling intelligent operation to gauge the surgical knot tying.

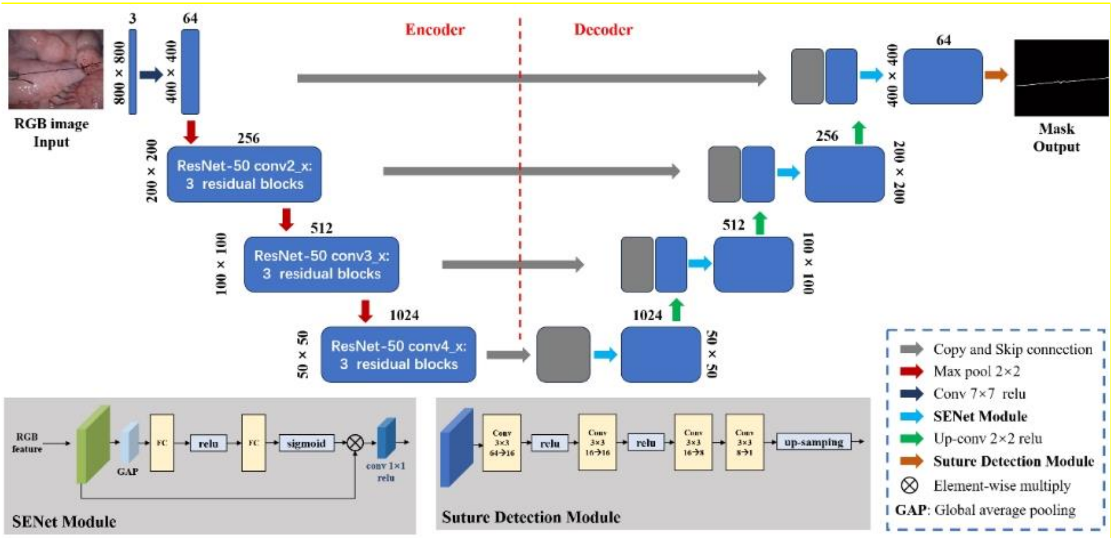

Fig. R18 (added in revised Supplementary Materials as Supplementary Fig. 31): The architecture of the proposed SlipknotNet. It is an encoder-decoder neural network, in which the image encoder is realized by pretrained ResNet50 and the decoder contains up-convolution operators, SENet modules, and a suture detection module.

Thirdly, for the automatic-braking function, once an opened slipknot is detected, the controller issues a stop command immediately, arresting instrument motion within 0.062 mm—well inside the 4.379 ± 0.263 mm buffer zone (defined as the released length when the sliputure is relaxed). The integrated system has been validated in both live porcine colonic defects repair (**Fig. R19**) and silicone practice models (**Fig. R20**), confirming the reliable performance through visual force feedback and enhancing the applicability in robotic surgery. Notably, during the simple-background silicone experiment, we directly convert RGB images into grey images without sliputure detection to detect slipknot status and achieve the expected performance.

We have added the robotic automatic-braking function in **Results** (Page 11, Line 230 to Page 12, Line 241): "The sliputure is designed to work with the current robotic systems, which is not equipped with dedicated force sensors…, This integrated system was validated in both silicone models and *in vivo* porcine colonic defect repairs, confirming its reliable performance through visual force feedback, and significantly enhancing sliputures' applicability in robotic surgery (**Fig. 4d, e**, **Supplementary Fig. 18, Video 11, 12**)." Detailed information has been included in **Methods** and **Supplementary Materials**.

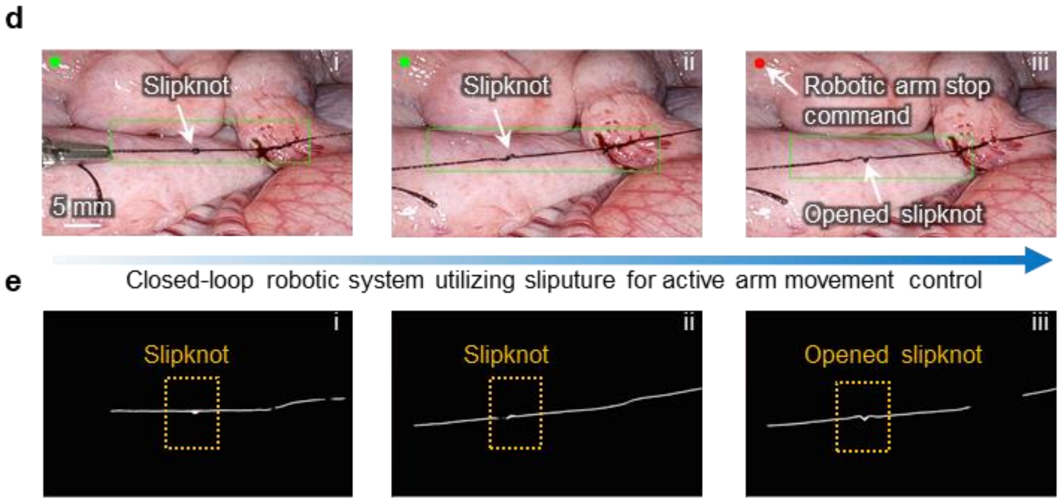

Fig. R19 (added in revised Manuscript as Fig. 4d, e): Slipknot gauges the intelligent operation of robots. d, Validation of the vision-based automatic-braking experiment in an *in vivo* porcine model. Real-time image processing for slipknot detection. Upon slipknot open, a stop command was activated to terminate the robotic movement. Scale bar, 5 mm. **e,** The slipknot was recognized from the RGB images and converted into real-time grey images. The slipknot opening was detected by matching the images to opened slipknot configuration.

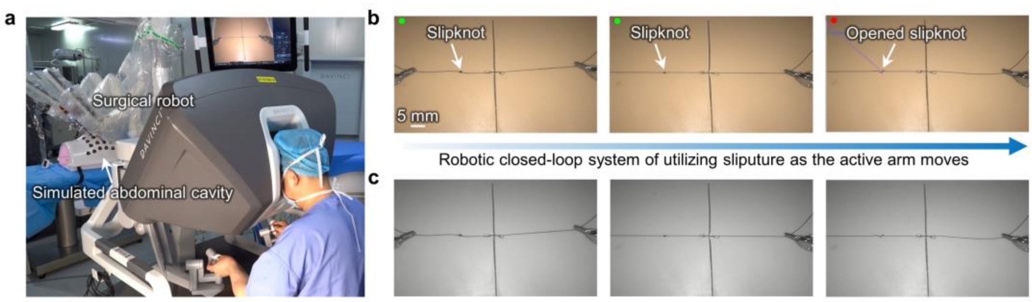

Fig. R20 (added in revised Supplementary Materials as Supplementary Fig. 18): Validation of the vision-based automatic-braking experiment in the silicone practice model. a, The surgeon employs sliputures to repair the silicone practice model using the Da Vinci robotic system under real-time monitoring. **b, c,** The system-triggered red stop marker was activated upon slipknot opening as the active arm moves on the silicone practice model.

- The paper dedicates most of its content to demonstrating the slipture technique's potential in surgical applications, which makes the concluding focus on its multiscale potential feel somewhat disconnected. While the multiscale possibilities are interesting, they diverge from the core narrative of the surgical focus, concluding in a less cohesive. To improve this, I see two options:
1. The conclusion should better align with the main theme of the paper by emphasising how the multiscale applications build on the surgical findings. For instance, the authors could frame the multiscale potential as a natural extension of successful surgical applications, highlighting the practical clinical success first and then transitioning to the broader impacts of the technique across various scales. Additionally, expanding on how the surgical outcomes demonstrate the robustness and versatility of the slipknot mechanism could provide a smoother transition to discussing its multiscale applicability.
2. Presenting the surgical results as a proof-of-concept could contextualise the technique's broader potential more effectively. Framing the paper as a focus on the general applications of the slipknot technique would be possible. However, multiple applications would need to be explored at a depth similar to that of surgery in order to feel balanced.

Response: Thanks for the suggestion. We sincerely agree with the first option that emphasizes how the multiscale applications build on the surgical findings, and then transitioning to the broader impacts of the technique across various scales. We believe this would expand the breadth and depth of interest.

The success of sliputure in clinical applications has led us to explore its potential to precisely control output force across different scales, ensuring the protection of delicate objects. We engineered a sliputure mechanical fuse by embedding a pre-programmed slipknot tendon into a tendon-driven robotic arm. Functionally, sliputure serves as a purely mechanical safety element, comparable to an electrical fuse or shear pin, yet without the need for additional electronics or increased mass on the end-effector and can be seamlessly integrated into robots.

We have added the content in **Discussion** (Page 13, Line 276 to Page 14, Line 281):
"We extend this mechano-intelligent strategy in robotic design to enhance safety…, This system can be implemented in various robots, to prevent structural overload, and ensure safe operation during human-robot interactions."

The additional experiment results have been revised in **Fig. 4f-h**

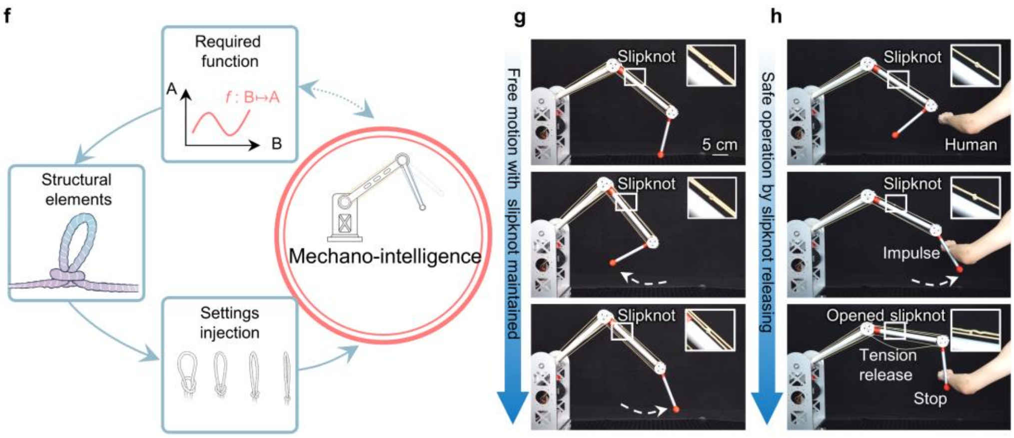

Fig. R21 (revised as Fig. 4f-h in Manuscript): Slipknot gauges the intelligent operation of robots. f, Protocol and methods of slipknots gauged mechanical transmission. **g, h,** Slipknot-enhanced safe human-robot interactions. **(g)** The proposed slipknot-integrated tendon-driven robotic arm demonstrates free motion capability at elbow and wrist joint with slipknot maintained. **(h)** During human robot interaction, slipknot is opened and releases the tension when the robot is overloaded by mishandling, guarding safe operation.

Minor Comments:

- Please clarify whether monofilament or braided sutures were used in the knot-tying force tests involving junior and senior surgeons.

Response: In the knot-tying force tests, both sliputures and common sutures were produced based on braided sutures (4-0 Mersilk, Ethicon, USA). And we have added the content in Knot tying force test across surgeons Part of **Methods** (Page 35, Line 625-626): "(1) the desired sliputure with a slipknot on braided common suture (4-0 Mersilk, Ethicon, USA).".

- While the visual feedback mechanism for minimally invasive surgery is promising, it would be helpful to include more detail on how this can be practically implemented in surgery with the high likelihood of occlusions from blood, etc.

Response: Thanks for your comment. Intraoperative bleeding resulting in visual occlusion is a relatively common situation in minimally invasive surgery[10]. This is typically managed by the surgeon or assistant either clamping the bleeding vessel followed by suctioning the accumulated blood, or directly using a suction device to clear the field and restore visibility[11]. These manipulations do not compromise sliputure integrity or functionality, which remains fully viable in such scenarios.

Notably, your valuable comment inspired us to consider how to practically implement sliputures in scenarios where the surgical field is partially or entirely occluded due to intraoperative bleeding. To address this challenge, we can modulate the length of the sliputure and reposition the slipknot along the suture, enabling the slipknot outside the region affected by blood during the knot tying. By maintaining the slipknot within a clear field, this approach enhances the reliability and safety of sliputure application under suboptimal surgical conditions.

We have added the content in **Discussion** (Page 13, Line 269-271): "Sliputures maintain their functionality even when the slipknot is positioned far from the surgical site, allowing it to remain outside areas affected by blood occlusion during suturing."

- The paper briefly mentions the stability of the slipknot over time (up to 32 days). Expand the reasoning for this and its relevance, especially for long-term suture reliability for surgery, given that the sliptures must be pre-tied to a specific force.

Response: The sliputures in this study are prepared prior to their use in hospitals, rather than being fabricated by surgeons in the operation rooms. In practice, there is typically a time interval between the production of sutures and their eventual use in surgery. To investigate whether the structure of sliputures changes during this period, potentially affecting F_{peak} and their performance, we evaluated the stability of the slipknot over time. The results demonstrate that the structural integrity and functionality of sliputures remain consistent throughout this period.
We have added the reason in **Results** (Page 6, Line 122 to Page 7, Line 124): "Notably, the slipknot retains its performance after 32 days of storage, demonstrating its long-term mechanical stability to support slipknot use from production to practical deployment (**Fig. 2h**)."

- The results for the knotting force in senior surgeons are missing. Adding this and statistical evidence is needed to back up the claim that the junior surgeons can surpass the senior.
- The comparison between junior and senior surgeons' performance with sliptures could be expanded slightly, explaining how this translates into clinical practice. For example, would you expect these to be replacements or as a training tool, as the data seems that senior surgeons have learned comparable accuracy without the sliptures' visual cue, similar to force applications in robotic surgery with/without haptics. My assumption is based on just looking at the graph; the stat analysis from the previous point will be necessary.

Response: We have added the results for the knotting force in senior surgeons. In the study, the knotting force in seniors using sliputures were 1.480 ± 0.272 N with $V_{\sigma}^{Seniors, Sliputure}$= 0.184. Additionally, we introduced $|\Delta F|$, defined as the absolute difference between actual and target F_{peak}, to expand the comparison between junior and senior surgeons' performance with sliputures. We found that seniors exhibited higher precision of knot tying using common sutures, while after using sliputures, juniors exhibited better performance than before and even achieve equivalent performance to seniors with sliputures (P = 0.165) and common sutures (P = 0.927). We have added the content in **Results** (Page 8, Line 151-161): "To expand the comparison between junior and senior surgeons' performance with sliputures, we introduced $|\Delta F|$, defined as the absolute difference between actual and target F_{peak}. Remarkably, using a sliputure with target F_{peak} of 1.400 N (F_{tying} = 0.350 N), juniors exhibited better performance than before (1.445 ± 0.280 N, $V_\sigma^{Juniors,\ Sliputure}$ = 0.194) ($|\Delta F|_{Juniors,\ Sliputure}$ = 0.238 ± 0.151 N *vs.* $|\Delta F|_{Juniors,\ Common\ Suture}$ = 0.575 ± 0.556 N, $P < 0.001$), while no significant influence was shown on seniors (1.480 ± 0.272 N, $V_\sigma^{Seniors,\ Sliputure}$ = 0.184) ($|\Delta F|_{Seniors,\ Sliputure}$ = 0.197 ± 0.201 N *vs.* $|\Delta F|_{Seniors,\ Common\ Suture}$ = 0.236 ± 0.204 N, $P = 0.349$). Furthermore, junior surgeons with sliputures even achieve equivalent performance to seniors with sliputures ($P = 0.165$) and common sutures ($P = 0.927$) (**Fig. 3d**)."

Besides, although senior surgeons achieved comparable accuracy without the sliputures' visual cue in the study, we envisioned the sliputures not only as a training tool but also as potential replacements for existing surgical sutures in knot tying. Sliputures can assist in consistently tying high-quality knots, particularly benefiting junior surgeons and those practicing in underdeveloped areas with limited medical resources and training. And we added the content in **Discussion** (Page 13, Line 272-275): "Sliputures can serve not only as training tools but also as practical replacements for conventional surgical sutures, particularly benefiting resource-limited regions with restricted access to medical equipment and training."

- A brief comment on the cost-effectiveness of the slipture, especially compared to electronic force-sensing alternatives, would further highlight its benefits for surgery

Response: Thanks for your valuable suggestions. We have incorporated the above comment into **Discussion** (Page 12, Line 254 to Page 13, Line 258): "Sliputures overcome these constraints via a mechano-intelligent design that requires no advanced materials or electronics…, Given the substantial cost of electronic force-sensing devices, easy-fabricated sliputures are highly economic, functioning without additional cost or attachment."

Referee #5 (Remarks to the Author):

The article notes a feature of the common slipknot that it acts as a mechanical force limiter in the transmission of force between the free ends of the line. An interesting application of this feature to the tying of sutures in surgical operations is studied in detail, with reasonable experimental evidence of the quality and repeatability of the force-limiting behavior and the effects of improved force regulation during suture tying on some outcomes such as post-surgical tissue blood supply, complication rates, and healing rates.

The paper really addresses three conceptually separate contributions; first, the idea of the "slipknot" as an implementation of a force-limiting mechanical structure; second, the application of that concept to surgery; and third, to provide evidence that regulation of the force during suture tying results in superior surgical outcomes. While the paper is interesting, it is not clear that all three of these contributions are fully explored yet.

Response: Thanks for your appreciation. Based on your valuable comments, we have made corrections point by point. We believe that the quality of our manuscript was significantly improved.

The first contribution is interesting. The idea that a peak force will occur when opening the slipknot is self-evident. The part which is not self-evident is that the peak force can be reliably programmed. Relatively good agreement is shown between models and experiment, and the strong but simple relationship between Fpreset and Fpeak is a useful observation. The experimental validation provides some basis to trust the analysis conducted using the models.
However, it would appear that friction, plasticity, and other complicated physical phenomena can affect the force required to open the knot. Presumably, in other materials, effects such as cohesion could play a role. Other than the initial tying force, the paper does not provide experimental evidence to validate the model-based understanding of the role of these other physical phenomena in producing precise peak forces.

Response: We greatly appreciate your valuable comments. The factors including friction, plasticity, and cohesion would indeed affect the force required to open the knot. In the framework of our model, friction has been considered as a primary factor. We have further conducted friction tests and tensile tests characterizing the friction of different filaments in various media. The results were consistent with our theoretical predictions.

We also found that plasticity primarily influences the preset stage, keeping the knot loop tight. In FEM simulation, both elastic and plastic effects are considered. Elasticity is simplified as linear elasticity, and plasticity is simplified as nonlinear isotropic/kinematic hardening model. In order to intuitively observe the effect of plasticity on the process of knot tightening and unloading, we simulate the model without plasticity. When the F_{tying} is released, the knot loop relaxes and gradually expands, the knot is opened when the knot loop exceeds the slip loop (**Fig. R22a**). With plasticity, the knot loop of the slipknot remains tight after F_{tying} is released (**Fig. R22b**). In our theoretical model, we presume that the slipknot remains at the state when F_{tying} is released and calculated F_{peak} without considering the plasticity. The hypothesis may cause significant error if the mechanical property of filaments is dominated by plasticity, which deserves further study. In current paper, we studied filaments including PTFE monofilament, braided absorbable sutures (Vicryl), and braided non-absorbable sutures (Mersilk), their properties are elastically dominated, and the model predicts the F_{peak} reliably.

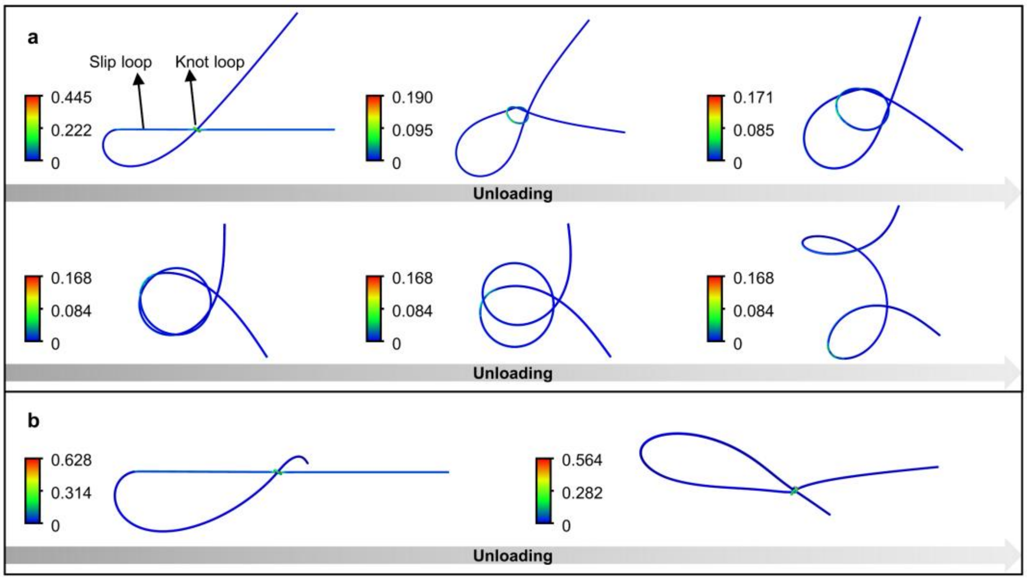

Fig. R22 (added in revised Supplementary Materials as Supplementary Fig. 33): Effect of material plasticity on slipknot mechanics in FEM. a, Simulation of tying a slipknot with pure elastic material. When the tying force F_{tying} is released, the knot loop relaxes and gradually expands, the knot is opened when the knot loop exceeds the slip loop. **b**, Simulation of tying a slipknot with elastic-plastic material. The knot loop of the slipknot remains tighten after the release of F_{tying}. The color bars denote max principal strain.

The cohesion within the filament would introduce an energy barrier to overcome before the knot slide. The force required to overcome the cohesion energy barrier follows that required to rupture two bonded filaments in a lap shear setup. The force is obtained by[12]:

$$F_{max} = \tau w L, \tau = \sqrt{\frac{2\mu G}{h}}.$$

Once the energy barrier is overcome, the filaments slides requiring negligible friction force (**Fig. R23**). Sliding occurs previous to the sliputure release, and we discovered several peak forces previous to the F_{peak} in the force-displacement curve, when the cohesion strength is enhanced by applying adhesives on the slipknot (**Fig. R24**), which attributes to the cohesion within the filament.

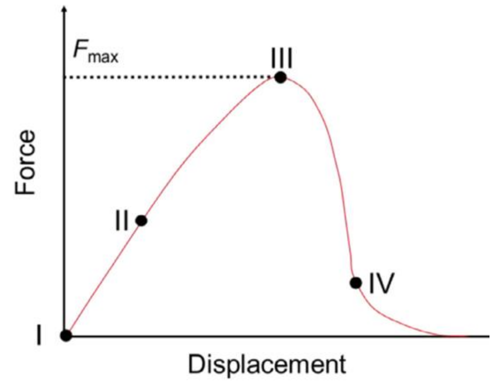

Fig. R23: Force-displacement curve using lap shear to measure cohesion strength. The strength is defined as the maximum force divided by the initial area of the adhesive joint.

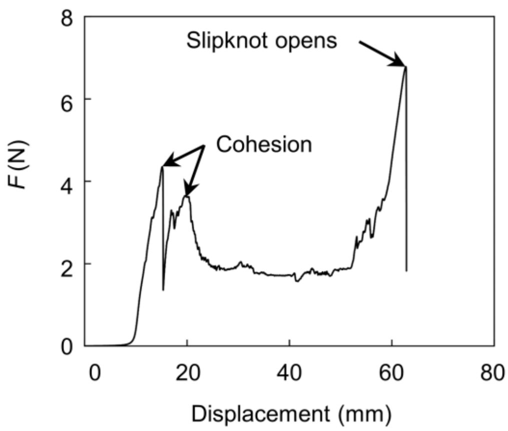

Fig. R24 (added in revised Supplementary Materials as Supplementary Fig. 37): The typical force-displacement curve of a filament with cohesion. When adhesives (Scotch permanent glue stick, 6015, 3M) are applied on the slipknot to enhance the cohesion strength, several force peaks are detected at the start. Sliding occurs prior to the sliputure release, and we discovered several peak forces prior to the F_{peak} in the force-displacement curve, which attributes to the cohesion within the filament. The small peak forces can be obtained as follows: $F_{max} = \tau wL, \tau = \sqrt{2\mu G/h}$, where τ is defined as the interface shear strength, w and L are the width and length of the area of adhesion, μ and h are the shear modulus and thickness of the filament, G is the energy release rate.

We have added studies about plasticity and cohesion in **Supplementary Materials**:
"**Effects of plasticity in knotting**

We found that plasticity primarily influences the preset stage, keeping the knot loop tight…, With plasticity, the knot loop of the slipknot remains tighten after the release of F_{tying}"

(Page 60): "Sliding occurs previous to the sliputure release…, G is the energy release rate."

The choice to explore the effects of the time after setting (Fig. 2h) and speed of pulling the knot (Fig 2i) seems odd since no physical phenomena were hypothesized by which these variables should play a role.

Response: The sliputures in this study are prepared prior to their use in hospitals, rather than being fabricated by surgeons in the operation rooms. In practice, there is typically a time interval between the production of sutures and their eventual use in surgery. To investigate whether the structure of sliputures changes during this period, potentially affecting F_{peak} and their performance, we evaluated the stability of the slipknot over time. The results demonstrate that the structural integrity and functionality of sliputures remain consistent throughout this period. Besides, each surgeon has his/her own habits, they would pull a knot by different speed. The sliputure fails to limit force if the opening force varies with the pulling speed. We demonstrate that within the pulling speed range of 10-80 mm/min, the opening force remains stable.

We have added the reason in **Results** (Page 6, Line 122 to Page 7, Line 124): "Notably, the slipknot retains its performance after 32 days of storage, demonstrating its long-term mechanical stability to support slipknot use from production to practical deployment (**Fig. 2h**)."

It is in particular odd that the conclusion is that the slipknot can reliably gauge operations without influence from the working environment. Is this true if the slipknot is characterized in a dry environment and then used in a wet one? Supplementary Fig. 20 seems to cast doubt on this since the friction parameter f2 has a significant impact on the force Fopen.

Response: Thank you for the comment. Referee #4 also raised the concern about friction in different environments. We have conducted additional experiments characterizing the static friction of three filaments (PTFE monofilament, braided absorbable sutures (Vicryl), and braided non-absorbable sutures (Mersilk)) in four media (synthetic blood, simulated body fluid, natural saline, and silicone oil). The frictional coefficient parameter μ was tested through the apparatus described in **Fig. R25a**, and the parameter f_2 originates from the corresponding tensile tests of the slipknot (**Table R8-10**).

We have added the content in **Results** (Page 6 Line 119-122): "Slipknots of different materials and structures, when submerged in various liquid media, exhibit different friction coefficients (**Supplementary Fig. 5**). This variation subsequently affects F_{peak} aligning with the model prediction (**Supplementary Fig. 6**)."

We also have added a new section in **Supplementary Materials** as follows:

Opening sliputures under dry, moist, and lubricated conditions

Surgical environments introduce variables such as moisture and lubrication that could alter the slipknot's performance regarding frictional behavior and tensile force limits. To understand this, we further studied the influence of friction in several filaments when they are in different working environments. Specifically, experiments characterizing the static friction of three filaments (PTFE monofilament, braided absorbable sutures (Vicryl), and braided non-absorbable sutures (Mersilk)) in four media (synthetic blood, simulated body fluid, natural saline, and silicone oil) were conducted. The frictional coefficient parameter μ was tested through the apparatus described in **Supplementary Fig. 5a**, and the parameter f_2 is derived from the corresponding tensile tests of the slipknot (**Supplementary Table 2-4**).

We measured the friction coefficient of the lines in various volumes of liquids (**Supplementary Fig. 5b-e**). The friction coefficients of PTFE fluorocarbon string and Vicryl exhibited little change (< 10%) in synthetic blood, simulated body fluid, and natural saline as compared to the dry condition. However, in silicone oil, the friction coefficients of PTFE decreased by 27.737%, and that of Vicryl increased by 14.805%, respectively. The friction coefficient of Mersilk was approximately 100% higher in synthetic blood, simulated body fluid, and natural saline than that in the dry condition, while it decreased by 17.853% in silicone oil.

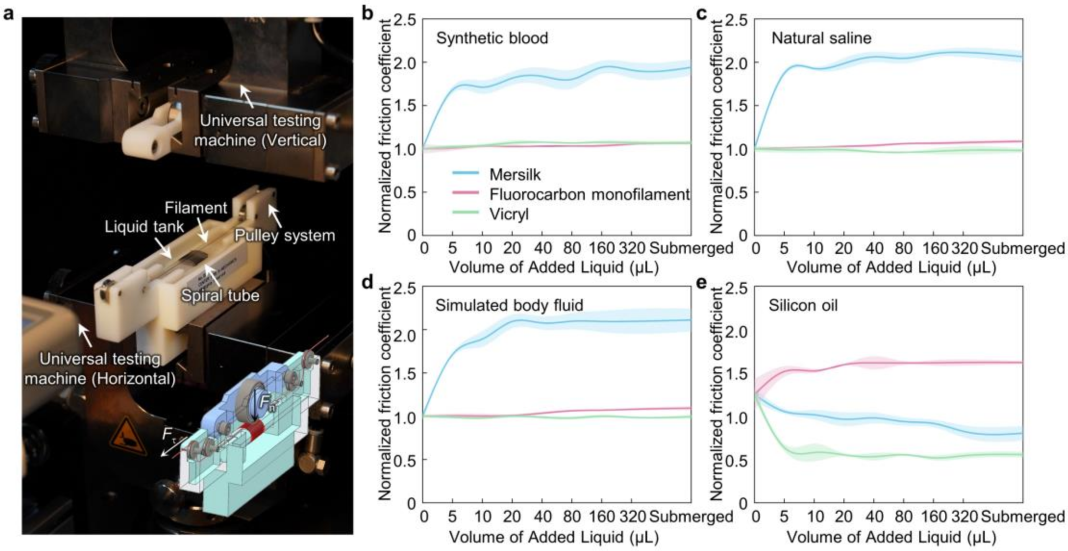

Fig. R25 (added in revised Supplementary Materials as Supplementary Fig. 5): Measurement of the friction coefficient of filaments in moist and lubricated conditions. a, The filament friction measurement setup in liquid environments. The pulley system allows the filament to be immersed in the tank with varying amounts of liquid. The testing machine (vertical) applies a normal force, F_n, pressing the filament firmly against a spiral tube wrapped with a single layer of the same filament. The testing machine (horizontal) pulls the single filament steadily, allowing the measurement of the tangential force, F_τ. **b-e,** Normalized friction coefficient of Mersilk, fluorocarbon monofilament, and Vicryl in various volumes of (**b**) synthetic blood, (**c**) natural saline, (**d**) simulated body fluid, and (**e**) silicone oil.

We next tested F_{peak} of the slipknots when they were submerged in different liquids and fabricated with various values of F_{tying} (**Supplementary Fig. 6**). F_{peak} of PTFE monofilament sliputures exhibited no measurable change in the three aqueous media (synthetic blood, simulated body fluid, natural saline), while a remarkable reduction in silicone oil; F_{peak} of Mersilk sliputures exhibited a slight increase in three aqueous media and some reduction in silicone oil; and F_{peak} of Vicryl sliputures increased in all four liquids, with the largest increment in silicone oil. We found that the theoretical model is applicable for predicting the peak force of slipknots fabricated from both monofilament filaments and braided sutures, and the results largely mirror the friction trends predicted by the analytical model (**Supplementary Table 5-8**), particularly in silicone oil, where the model accurately predicted the increase and decrease for all three filaments. However, for Mersilk in aqueous media, the theoretical outcome leads to a higher prediction increase compared to the actually measured increase. Such discrepancy is potentially due to the model not accounting for the effect of swelling on the radius of constraint, R, in Eq. (S30), which could overestimate the peak force.

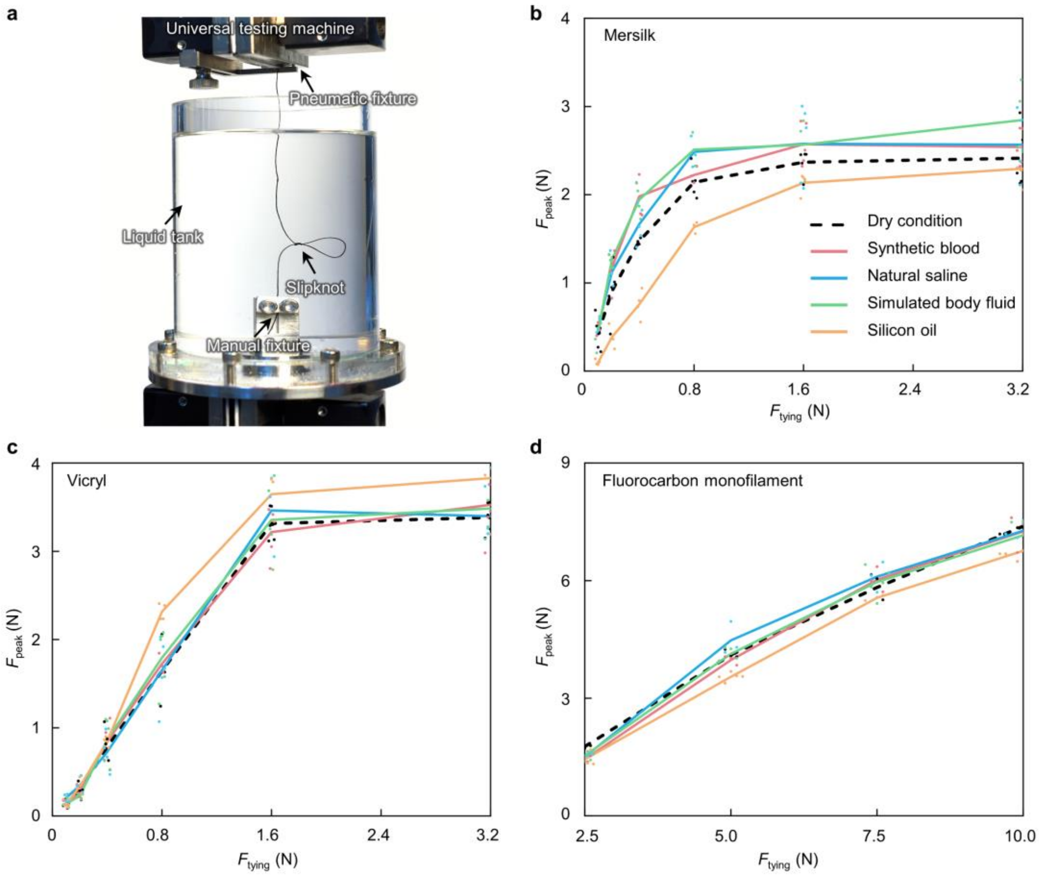

Fig. R26 (added in revised Supplementary Materials as Supplementary Fig. 6): Measurement of the relationship between F_{peak} and F_{tying} of sliputures in dry,

moist and lubricated conditions. a, The uniaxial stretching setup in liquid environments. The manual fixture at the bottom presses the sliputure into the groove and is screwed into the pre-threaded section in the liquid tank to ensure coaxiality during the tensile test. The upper and lower fixtures are brought as close as possible before starting the test to minimize the effect of buoyancy. **b,** The relationship between F_{peak} and F_{tying} for sliputure made with Mersilk in synthetic blood, natural saline, simulated body fluid, and silicone oil. **c,** The relationship between F_{peak} and F_{tying} for sliputure made with Vicryl in synthetic blood, natural saline, simulated body fluid, and silicone oil. **d,** The relationship between F_{peak} and F_{tying} for sliputure made with fluorocarbon monofilament in synthetic blood, natural saline, simulated body fluid, and silicone oil.

Table R8 (added in revised Supplementary Materials as Supplementary Table 2): Parameters of PTFE monofilament sliputures in silicone oil and dry condition.

Conditions	E (GPa)	d (mm)	μ	f_2 (F_{tying} = 2.500 N)	f_2 (F_{tying} = 5.000 N)	f_2 (F_{tying} = 7.500 N)	f_2 (F_{tying} = 10.000 N)
Dry	2.700	0.235	0.165	0.543	1.649	2.862	3.900
Silicone oil	2.700	0.235	0.119	0.547	1.380	2.666	3.393

Table R9 (added in revised Supplementary Materials as Supplementary Table 3): Parameters of Mersilk sliputures in silicone oil, synthetic blood, and dry condition.

Conditions	E (GPa)	d (mm)	μ	f_2 (F_{tying} = 0.400 N)	f_2 (F_{tying} = 0.800 N)	f_2 (F_{tying} = 1.600 N)	f_2 (F_{tying} = 3.200 N)
Dry	9.745	0.150	0.145	0.246	0.442	0.713	0.763
Silicone oil	9.745	0.150	0.119	0.065	0.233	0.374	0.548
Synthetic blood	9.745	0.150	0.260	0.328	0.622	1.104	1.125

Table R10 (added in revised Supplementary Materials as Supplementary Table 4): Parameters of Vicryl sliputures in silicone oil and dry condition.

Conditions	E (GPa)	d (mm)	μ	f_2 (F_{tying} = 1.600 N)	f_2 (F_{tying} = 3.200 N)
Dry	14.668	0.150	0.157	0.551	0.611
Silicone oil	14.668	0.150	0.180	0.521	0.591

Table R11 (added in revised Supplementary Materials as Supplementary Table 5): The comparison of F_{peak} of PTFE monofilament sliputures in silicone oil and dry condition.

F_{tying} (N)	Exp.- dry (N)	Exp.- liquid (N)	Theory-dry (N)	Theory-liquid (N)
2.500	1.766	1.439	1.970	1.646
5.000	4.104	3.548	3.371	2.655
7.500	5.826	5.563	4.864	4.179

10.000	7.388	6.763	6.115	5.026

Table R12 (added in revised Supplementary Materials as Supplementary Table 6): The comparison of F_{peak} of Mersilk sliputures in silicone oil and dry condition.

F_{tying} (N)	Exp.-dry (N)	Exp.-liquid (N)	Theory-dry (N)	Theory-liquid (N)
0.400	1.517	0.756	1.978	1.516
0.800	2.142	1.633	2.226	1.721
1.600	2.368	2.135	2.568	1.894
3.200	2.414	2.295	2.631	2.107

Table R13 (added in revised Supplementary Materials as Supplementary Table 7): The comparison of F_{peak} of Mersilk sliputures in synthetic blood and dry condition.

F_{tying} (N)	Exp.-dry (N)	Exp.-liquid (N)	Theory-dry (N)	Theory-liquid (N)
0.400	1.517	1.979	1.978	3.538
0.800	2.142	2.223	2.226	3.962
1.600	2.368	2.571	2.568	4.647
3.200	2.414	2.540	2.631	4.677

Table R14 (added in revised Supplementary Materials as Supplementary Table 8): The comparison of F_{peak} of Vicryl sliputures in silicone oil and dry condition.

F_{tying} (N)	Exp.- dry (N)	Exp.- liquid (N)	Theory-dry (N)	Theory-liquid (N)
1.600	3.316	3.647	3.391	3.733
3.200	3.383	3.829	3.468	3.826

Lastly, it is not clear what the DNA simulation is supposed to convey. The literature already contains plenty of references to slipknots in DNA. As already stated, the fact that the knot would require a peak force to open and that this force will depend on how tightly the knot is tied is relatively straightforward, so it is not clear to me what the need is for "validation" spanning geometric scales. This line of reasoning does not make the paper more "scientifically valid" and doesn't seem to serve a clear purpose in the context of the rest of the paper.

Response: Thanks for your comments. We had conducted DNA simulation to support that the peak force mechanism in slipknot still work at nano scale with ultra small force. This representative example of knots at the molecular scale may give some inspirations for broad cross-scale applications. We agree that the DNA simulation serves more as an illustrative extension rather than contributing directly to the scientific rigor of the main study, and we have moved it to the Supplementary materials. Only a brief discussion about the DNA simulation is selected in **Discussion** (Page 14, Line 285-288): "The mechano-intelligence exhibited in slipknots may inspire investigations of knotted structures across multiple length scales. The opening of slipknotted DNA molecules showcases how mechanical transmission behaviors can be gauged at the nanoscale."

The second contribution is also an interesting one. However, if the paper's aim were only to solve this "engineering" problem of limiting suture tension, then other potential solutions might be competitive, limiting the significance of this contribution. Sacrificial mechanical features/components to serve force- or torque-limiting design functions have been a common strategy for a long time (e.g., the common shear pin). Other obvious strategies would be to produce sutures that break at the desired tension or to grasp the suture with a tool with a controlled gripping force on the suture. Perhaps there is something superior about the slipknot as a solution, but since no other solutions are even qualitatively explored or discussed, the paper leaves the feeling that the paper might be presenting a novel solution to the problem for the sake of its novelty alone rather than its advantages. With that said, the strategy does appear to work.

Response: Thanks for your comment. To sense and encode force, modern machines and robots typically use complex electronic devices[13,14], which meet challenges under circumstances short of operating space and resources, such as minimally invasive surgerie[15-17] and operations in remote areas without electricity. Strategies in surgery like designing sutures that break at the desired tension or using tools that apply controlled gripping forces to the suture might work. While there is something superior about the slipknot as a solution, the slipknot strategy not only introduces novelty but also offers practical advantages.

Minimally invasive is a representative and challenging application scenario for sliputures. It has limited operating space, narrow operating access for electronic devices to feedback force make in surgery[6]. Sliputures offer a mechano-intelligent solution to these limitations with following advantages: 1) sliputures is based on fabricating an engineered slipknot on common sutures, do not require additional advanced material or electronics. It is accessible to area where medical conditioning is poor. 2) it is not necessary for surgeon to change their operation habits during surgery, they can also further adjust the tension after the sliputure is released, if they think more tension is required based on their clinical experience. 3) the sliputure release does not generate wastes that may cost further operation to clean. 4) the sliputure can be easily integrated with robots for safety and precision clinical operations. And we have added the content in **Discussion** (Page 12, Line 251 to Page 13, Line 269): "This mechanism is particularly well-suited for minimally invasive surgery, a representative application for sliputures, where limited operating space and restricted access to electronic devices present significant challenges. Sliputures overcome these constraints via a mechano-intelligent design that requires no advanced materials or electronics…, Given the substantial cost of electronic force-sensing devices, easy-fabricated sliputures are highly economic, functioning without additional cost or attachment…, The strategy is compatible with robotic systems to provide intelligent operation."

Further comparison between sliputures and other force limiting strategies have been included in **Supplementary Materials**: "We considered several strategies that might be applied to limit the tension of sutures..., We summarize a table (**Supplementary**

Table 1) to compare those structures with the sliputure. Sliputures feature simplicity, high precision, low-cost, and residue-free."

Table R15 (added in revised Supplementary Materials as Supplementary Table 1): Comparison of sliputure versus force-limiting devices.

Device type	Breakaway coupling	Friction clutch	Belleville washer	Mechanical fuse	Shear pin	Sliputure
Operating principle	Predesigned weak point fractures upon overload	Friction surfaces slip beyond preset torque	Conical spring deforms elastically under load	Fractures or deforms irreversibly at overload	Shears at predetermined torque or force	Slipknot releases at peak force
Overload response	Irreversible disconnection	Reversible slipping	Elastic displacement; Non-destructive	Irreversible failure	Instantaneous irreversible failure	Slipping with dual visual and mechanical cue
MIS trocar compatibility (5-12 mm)	Bulky; Rigid; Metallic	Mechanically complex; Non-flexible	Requires rigid support; Metallic	Difficult to miniaturize	Rigid; Space-occupying	Fully flexible; Trocar-compatible
Reusability	Single-use; Requires replacement	Slips and resumes functionality	Restores elastically	Single-use; Permanent deformation	Breaks permanently; Requires replacement	Multiple-use; Reloadable with F_{tying}
Residue	Broken components may remain	Risk of particulate debris	Potential fatigue fractures	Requires fragment removal	Leaves metallic debris	No debris; Native suture remains *in situ*
Imaging compatibility (MRI/CT)	Metallic housing artifacts	Metallic components disrupt imaging	Spring-metals artifacts	Metallic components interfere	Imaging artifacts	Completely artifact-free; Non-metallic
Cost & single-use suitability	Precision parts; Relatively expensive	High manufacturing complexity	Costly to mass-produce	Economical	Simple; Easily replaceable	Compatible with standard suture production; Negligible cost
Hardware or assembly requirement	Mechanical connectors required	Motor or drive integration required	Aligned preload assembly required	Fixture and housing required	Mechanical interface required	No additional hardware or assembly required
Biocompatibility	Industrial-grade metals; Inflammation or rejection risk	External-use; Non-biocompatible;	Non-implantable Metal; Tissue reaction	Non-implantable materials typically	Sharp fracture ends; Irritation risk	Fully biocompatible; Identical to surgical suture materials

MIS, Minimally invasive surgery; MRI, Magnetic resonance imaging; CT, Computed tomography.

The third contribution seems well supported by the evidence, but readers may naturally wonder if there are reasons why sutures are not currently tied with explicit tension measurement or regulation.

Response: We appreciate the reviewer's concern regarding the intraoperative quantification of suture tension. Explicit tension measurement or regulation remains challenging in current surgical practice. First, conventional tension measurement or regulation rely on electronic devices, which is difficult to accommodate within confined operating space of minimally invasive surgery and complicates operation procedure[13]. Second, quantitative mechanics in surgical training is not sufficiently aware. Surgeons prefer estimate suture tension visually based on tissue deformation rather than employing real-time mechanical assessment[18,19]. In the paper, we have developed a wearable real-time dynamometer in knotting tension measurement or regulation. However, its current form falls short of the practical demands of laparoscopic and robotic procedures.

For better specification, we have added the discussion of challenges in **Introduction** (Page 4, Line 64-66): "In surgical practice, explicit tension measurement remains demanding, as sensing systems are often impractical to implement, and surgeons typically rely on visual estimation from tissue deformation rather than quantitative assessment.".

The obvious and unaddressed question in the paper is whether the "feasible" range of tensions can be predicted reliably a priori. One presumes that the "feasible range" would need to be established carefully in human studies and that it may depend not only on the specific surgical procedure but possibly other patient-specific factors. The paper does not discuss this practical challenge to application.

Response: We appreciate the reviewer for highlighting this important point. The "feasible range" of tensions vary depending on the specific surgical procedure as well as patient-specific factors. In our study, the feasible range was determined based on a set of 20 experimental samples in total. We have not yet conducted experiments on human tissue, but we have extended mechanical models to predict the "feasible range". And we have added the discussion in **Results** (Page 9, Line 172-174): "The optimal knot tying force for future surgical procedures could be obtained by synergy of experimental tests and mechanical modelling (**Section: Feasible force range prediction in Supplementary Materials**)."

We have added the model in **Supplementary Materials**:

Feasible force range prediction

The feasible force range lies between two important values: the lower limit to prevent from dehiscence, and the upper limit to prevent from ischemia (**Fig. 3c**). These two values are determined through experiments in the main text. Here, we present two mechanical models that can be applied to provide estimation on these two values.

The lower tension limit is to prevent dehiscence. We apply the thin-walled column model for prediction (**Supplementary Fig. 36a**). Assume the diameter of the column is D, the thickness is δ, and it is filled with gas with inner pressure p, given that N stitches are applied in a suture area of A. The stress tensor can be expressed by:

$$\sigma = \begin{bmatrix} \sigma_1 & 0 \\ 0 & \sigma_2 \end{bmatrix}, \tag{S35}$$

where we have:

$$\sigma_1 = \frac{pD}{4\delta}, \sigma_2 = \frac{pD}{2\delta}, \tag{S36}$$

and the traction can be expressed by:

$$t = \sigma \cdot n. \tag{S37}$$

the force required in the suture to maintain the inner pressure is obtained as:

$$F = (\sigma_1 \sin^2\theta + \sigma_2 \cos^2\theta)A/N. \tag{S38}$$

The upper limit to prevent from ischemia. Here we adopt the model to predict the critical force of tearing the tissue (**Supplementary Fig. 36b**). The radius of the suture is R, and a tying force per unit length F is applied on center of the suture. Young's modulus and Poisson's ratio of the suture are E_1 and v_1, and those for the tissue are E_2 and v_2, respectively.

From previous work, the contact pressure $p(\theta)$ can be expressed by

$$\frac{p(\theta)}{F/R} = \frac{2\sqrt{b^2 - y^2}}{\pi\sqrt{b^2+1}(1+y^2)} + \frac{1}{\pi}\left(1 - \frac{B}{2}\right)\ln\left(\frac{\sqrt{b^2+1} + \sqrt{b^2 - y^2}}{\sqrt{b^2+1} - \sqrt{b^2 - y^2}}\right), \tag{S39}$$

where $y = \tan(\theta/2)$, and

$$B = \frac{2b^4 + 2b^2 - 1}{b^2(b^2+1)} \tag{S40}$$

The parameter b can be obtained through

$$\frac{(\alpha - 1)(\ln(b^2+1) + 2b^4) + 2}{\pi(1+\alpha)(b^2+1)b^2} - \frac{4\beta}{\pi(1+\alpha)} = 0, \tag{S41}$$

where α and β are defined through

$$\alpha = \frac{((\kappa_1+1)/\mu_1) - ((\kappa_2+1)/\mu_2)}{((\kappa_1+1)/\mu_1) + ((\kappa_2+1)/\mu_2)}, \beta = \frac{((\kappa_1-1)/\mu_1) - ((\kappa_2-1)/\mu_2)}{((\kappa_1+1)/\mu_1) + ((\kappa_2+1)/\mu_2)}. \tag{S42}$$

For plane stress situations, we have

$$\kappa_i = \frac{3 - v_i}{1 + v_i}, \mu_i = \frac{E_i}{2(1+v_i)}, \tag{S43}$$

and for plane strain situations, we take

$$\kappa_i = 3 - 4v_i, \mu_i = \frac{E_i}{2(1+v_i)}, \tag{S44}$$

The stress field at the contact surface $(r = R)$ is then given by

$$\sigma_{rr}(\theta) = -p(\theta), \sigma_{r\theta}(\theta) = 0, \tag{S45}$$

and

$$\sigma_{\theta\theta}(\theta) = -p(\theta) + \frac{3 - v_2^*}{2\pi}\cos(\theta) + \frac{\ln(b^2+1) + 2b^4}{\pi b^2(b^2+1)}. \quad \text{(S46)}$$

Note that we have $v_2^* = v_2$ for the plane stress situation, and we take $v_2^* = v_2/(1-v_2)$ for the plane strain case.

Converting the stress tensor into the *x*-*y* plane

$$\begin{cases} \sigma_{xx}(\theta) = \dfrac{\sigma_{rr} + \sigma_{\theta\theta}}{2} + \dfrac{\sigma_{rr} - \sigma_{\theta\theta}}{2}\cos(2\theta), \\ \sigma_{yy}(\theta) = \dfrac{\sigma_{rr} + \sigma_{\theta\theta}}{2} - \dfrac{\sigma_{rr} - \sigma_{\theta\theta}}{2}\cos(2\theta), \\ \sigma_{xy}(\theta) = \dfrac{\sigma_{rr} - \sigma_{\theta\theta}}{2}\sin(2\theta). \end{cases} \quad \text{(S47)}$$

The dimensionless von-Mises stress can then be expressed by

$$\sigma_M(\theta) = \sqrt{\frac{1}{2}\left(\begin{array}{c}\left(\sigma_{xx}(\theta) - \sigma_{yy}(\theta)\right)^2 + \left(\sigma_{yy}(\theta) - \sigma_{zz}(\theta)\right)^2 \\ +\left(\sigma_{zz}(\theta) - \sigma_{xx}(\theta)\right)^2 + 6\left(\sigma_{xy}(\theta)\right)^2\end{array}\right)}, \quad \text{(S48)}$$

where for plane stress condition, we have $\sigma_{zz}(\theta) = 0$, and for plane strain condition, we take

$$\sigma_{zz}(\theta) = v_2\left(\sigma_{xx}(\theta) + \sigma_{yy}(\theta)\right). \quad \text{(S49)}$$

The lower tension limit is obtained when the maximum of $\sigma_M(\theta)$ reaches the strength of a tissue $[\sigma]$, which can be represented by:

$$\max[\sigma_M(\theta)] = [\sigma]. \quad \text{(S50)}$$

One item not addressed by the paper is the type of knot that is being tied. Many different knots have been written about for surgical applications (see, e.g., [A], although the use of the term "slipknot" in that work refers to a knot which slides rather than slips open topologically).

[A] Shimi, S. M, et al., "Comparative study of the holding strength of slipknots using absorbable and nonabsorbable ligature materials", Surg Endosc, 1994, vol 8., pp. 1285-1291.

Response: Thanks for your comment. In the current paper, we employed sliputure to tie and secure surgeon's knots. The surgeon's knots is one of the most widely used knot types in surgery[20]. The sliputure has a slipknot termed "stopper knot". It is easily released by pulling on the free end, allowing the slip loop to collapse instantly[21]. The "stopper knot" could be constructed with various number of knot loops. Adjusting the number of knot loop enables regulation over F_{peak}, allowing it to be tuned to meet the demands of specific applications. We have revised "Afterward, a reverse knot was tied to secure the surgical knots (surgeon's knot)." in **Methods** (Page 40, Line 738-739) and "We recruit surgeons of varying seniority to tie a surgeon's knot for incision closure on a silicone practice model using the sliputure and common suture." in **Results** (Page 8, Line 146-148).

Additionally, sliputures are applicable to limit the knotting force of various surgical knots. We demonstrate application of sliputures in standardizing the locking/tightening forces of five other type of knots, including Tayside, Roeder, Melzer, Cross square, and Blood knots (**Fig. R27)**.

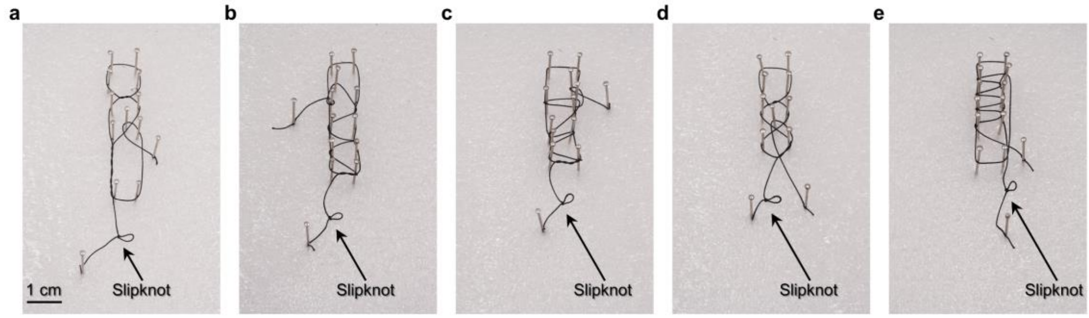

Fig. R27: Five sliding knots fabricated with engineered slipknots. a, Tayside knot with a slipknot. **b,** Roeder knot with a slipknot. **c,** Melzer knot with a slipknot. **d,** Cross square knot with a slipknot. **e,** Blood knot connect with a slipknot. Scale bar, 1 cm.

The strategy here seems to apply in only some circumstances, and it would be good if the paper were clearer about the scenarios in which the proposed solution would apply or not apply.

Response: In the current version, we have demonstrated that our strategy is applicable to gauge force in surgical knotting. We note that sliputures are applicable across a wide range of fields requiring mechanical transmission mechanisms to control the intelligent operation of either human or robotic systems. Notably, the prominent applications are found in the fields of surgery and engineering.

We have added discussion about the possible application scenarios in **Discussion** (Page 13, Line 262 to Page 14, Line 281): "Our sliputure strategy is applicable to both open and minimally invasive surgeries where limiting knotting force is critical. This includes procedures involving standing sutures in abdominal operations, particularly those performed in confined spaces such as anastomotic reconstruction of narrow luminal structures[41,42], as well as surgeries that demand precise knot tension, including corneal repair and vascular suturing[43]. The surgeons preserve conventional surgical habits using sliputures, without necessity of additional procedures to limit knotting force. The strategy is compatible with robotic systems to provide intelligent operation. Sliputures maintain their functionality even when the slipknot is positioned far from the surgical site, allowing it to remain outside areas affected by blood occlusion during suturing. The strategy is also compatible with continuous sutures (**Supplementary Fig. 17**), extending its applicability across diverse surgical scenarios. Sliputures can serve not only as training tools but also as practical replacements for conventional surgical sutures, particularly benefiting resource-limited regions with restricted access to medical equipment and training. We extend this mechano-intelligent strategy in robotic design to enhance safety. By integrating a programmed slipknot into the actuation pathway of a tendon-driven robotic arm (**Fig. 4f-h**), the system autonomously interrupts force transmission, acting as a fuse when the tensile load exceeds F_{peak}. This system can be implemented in various robots, to prevent structural overload, and ensure safe operation during human-robot interactions."

(Page 14, Line 288-291): "Slipknots act as mechano-intelligent mediators in situations where filaments are used. The mechanical information embedded in other structural elements remains to be discovered, promoting the mechano-intelligence to broader applications."

Additionally, some important information about some of the experiments is missing. In the description of the methods for the comparison of anastomotic leakage, postsurgical adhesion, and tissue ischemia, it is not clear who performed the trials not involving the sliputure (i.e., relationship to the authors, level of experience, whether the surgeon tying the common sutures was blinded to the purpose of the study, etc.).

Response: We have added the clarifications of surgeon who performed the comparison experiments of anastomotic leakage, postsurgical adhesion, and tissue ischemia in **Methods** (Page 40, Line 749 to Line 753): "The experimental procedures were performed by a junior surgeon with 2 years of clinical experience. This surgeon was affiliated with Department of General Surgery of another tertiary hospital and had no conflict of interest. To minimize bias, the surgeon was blinded to the study objectives while tying the common sutures." And the surgeon has been appreciated in **Acknowledgements** for his assistance.

The discussion section of the paper has several weaknesses, in my opinion. The phrase "controlling force" is used haphazardly. The slipknot does not regulate the force; it can limit the force, but not control it in the technical sense (at least in the sense of the typical goals of standard control theory). Furthermore, the idea that designs can be enriched by incorporating tension and twist is a hypothesis even though it is stated as a fact. The same could be said of the link between precise and rapid mass production and the range of applications. It is also unclear how a slipknot would be applied in the context of body-sized humanoid robot movements since the knots can only be opened once. In general, the discussion is written in such a way that it claims more than it should, in my opinion, based on the evidence provided in the rest of the paper.
Ultimately, the work seems to mostly be of good technical quality, but the conclusions are not fully convincing because of some of the shortcomings noted above.

Response: Thanks for your comment. We have revised all "control" force as "limit" force throughout the manuscript. In addition, we have substantially revised the **Discussion** and we hope that the revised version addresses your concerns satisfactorily. (Page 12, Line 248 to Page 14, Line 291):

"**Discussion**

We propose a mechano-intelligent transmission mechanism based on the slipknot and validate its precision and robustness in delivering force signals for clinical practice and robotic operation (**Fig. 4f**). This mechanism is particularly well-suited for minimally invasive surgery, a representative application for sliputures, where limited operating space and restricted access to electronic devices present significant challenges[40]. Sliputures overcome these constraints via a mechano-intelligent design that requires no advanced materials or electronics. They offer advantages in simplicity and disposability over conventional force limiting devices (**Supplementary Table 8**). Given the substantial cost of electronic force-sensing devices, easy-fabricated sliputures are highly economic, functioning without additional cost or attachment. An automatic slipknot fabrication machine enables standardized and on-demand production, supporting scalable application (**Supplementary Fig. 21, Video 14**).

Our sliputure strategy is applicable to both open and minimally invasive surgeries where limiting knotting force is critical. This includes procedures involving standing sutures in abdominal operations, particularly those performed in confined spaces such as anastomotic reconstruction of narrow luminal structures[41,42], as well as surgeries that demand precise knot tension, including corneal repair and vascular suturing[43]. The surgeons preserve conventional surgical habits using sliputures, without necessity of additional procedures to limit knotting force. The strategy is compatible with robotic systems to provide intelligent operation. Sliputures maintain their functionality even when the slipknot is positioned far from the surgical site, allowing it to remain outside areas affected by blood occlusion during suturing. The strategy is also compatible with continuous sutures (**Supplementary Fig. 17**), extending its applicability across diverse surgical scenarios. Sliputures can serve not only as training tools but also as practical replacements for conventional surgical sutures, particularly benefiting resource-limited regions with restricted access to medical equipment and training. We extend this mechano-intelligent strategy in robotic design to enhance safety. By integrating a programmed slipknot into the actuation pathway of a tendon-driven robotic arm (**Fig. 4f-h**), the system autonomously interrupts force transmission, acting as a fuse when the tensile load exceeds F_{peak}. This system can be implemented in various robots, to prevent structural overload, and ensure safe operation during human-robot interactions.

We have developed a mechanical transmission strategy that harnesses a slipknot structure to enable intelligent operation in both clinical practice and robotic application. The mechano-intelligence exhibited in slipknots may inspire investigations of knotted structures across multiple length scales. The opening of slipknotted DNA molecules showcases how mechanical transmission behaviors can be gauged at the nanoscale (**Supplementary Fig. 22, Video 15**). Slipknots act as mechano-intelligent mediators in situations where filaments are used. The mechanical information embedded in other structural elements remains to be discovered, promoting the mechano-intelligence to broader applications."

References

1 Giles, D. & Talbot, E. in *Shackelford's Surgery of the Alimentary Tract, 2 Volume Set* 1005-1013 (Elsevier, 2019).

2 Law, W. *et al.* Single-layer continuous colon and rectal anastomosis using monofilament absorbable suture (Maxon®): study of 500 cases. *Diseases of the colon & rectum* **42**, 736-740 (1999).

3 Koruda, M. J. & Rolandelli, R. H. Experimental studies on the healing of colonic anastomoses. *Journal of Surgical Research* **48**, 504-515 (1990).

4 Lee, W. B. & Mannis, M. J. in *Ophthalmic microsurgical suturing techniques* 49-59 (Springer, 2007).

5 Brunner, M. *et al.* Continuous or interrupted suture technique for hepaticojejunostomy? A national survey. *BMC surgery* **18**, 1-7 (2018).

6 Duconseil, P. *et al.* Biliary complications after pancreaticoduodenectomy: skinny bile ducts are surgeons' enemies. *World journal of surgery* **38**, 2946-2951 (2014).

7 Pye, G. & Steele, R. Anastomoses involving the colon and rectum: an 8-year experience. *Journal of the Royal College of Surgeons of Edinburgh* **41**, 95-96 (1996).

8 Deen, K. & Smart, P. Prospective evaluation of sutured, continuous, and interrupted single layer colonic anastomoses. *The European Journal of Surgery Acta Chirurgica* **161**, 751-753 (1995).

9 Jain, S. K., Stoker, D. L. & Tanwar, R. *Basic surgical skills and techniques*. (JP Medical Ltd, 2018).

10 Ponsky, T. A., Khosla, A. & Ponsky, J. L. Minimally invasive surgery. *Textbook of Clinical Gastroenterology and Hepatology*, 1182-1189 (2012).

11 Flores, J. & Gregorcyk, S. G. in *Improving Outcomes in Colon & Rectal Surgery* 49-60 (CRC Press, 2018).

12 Wang, Y., Yang, X., Nian, G. & Suo, Z. Strength and toughness of adhesion of soft materials measured in lap shear. *Journal of the Mechanics and Physics of Solids* **143**, 103988 (2020).

13 Kim, U., Lee, D.-H., Yoon, W. J., Hannaford, B. & Choi, H. R. Force sensor integrated surgical forceps for minimally invasive robotic surgery. *IEEE Transactions on Robotics* **31**, 1214-1224 (2015).

14 Rothemund, P. *et al.* Shaping the future of robotics through materials innovation. *Nature Materials* **20**, 1582-1587 (2021).

15 Bandari, N., Dargahi, J. & Packirisamy, M. Tactile sensors for minimally invasive surgery: A review of the state-of-the-art, applications, and perspectives. *Ieee Access* **8**, 7682-7708 (2019).

16 Cheng, C. L. & Rezac, C. The role of robotics in colorectal surgery. *Bmj* **360** (2018).

17 De Rooij, T. *et al.* Laparoscopic pancreatic surgery for benign and malignant disease. *Nature reviews Gastroenterology & hepatology* **13**, 227-238 (2016).

18 Abiri, A. *et al.* Tensile strength and failure load of sutures for robotic surgery. *Surgical endoscopy* **31**, 3258-3270 (2017).

19 Abdi, E., Kulić, D. & Croft, E. Haptics in teleoperated medical interventions: Force measurement, haptic interfaces and their influence on user's performance. *IEEE Transactions on Biomedical Engineering* **67**, 3438-3451 (2020).

20 Kirk, R. M. *Basic Surgical Techniques E-Book*. (Elsevier Health Sciences, 2010).

21 Ashley, C. W. *The Ashley book of knots*. Vol. 13 (Doubleday, 1944).

Referee #1:
Referee #1 (Remarks to the Author):
No further comments, thank you for your answers.

Response: We thank Referee #1 for the feedback and for acknowledging our responses.

Referee #4 (Remarks to the Author):

The paper presents an updated manuscript focused on the use of slipknot-based mechanical limits in sutures. The "sliptures" are evaluated in a variety pof surgical scenarios (benchtop tests, phantom suturing, live animal models) inticating their potetnial for use as a low-cost force limiter in surgery.

The authors have made significant changes in response to previous reviewer comments, including the addition of several new experiments. These new experiments are rigorous and directly address the prior round of reviewer concerns. The work remains relevant and timely, and the updates strengthen the paper considerably.

The revisions have clearly improved the overall quality of the work. The expanded mechanical testing, including experiments across different suture materials and anatomical lubricants, helps solidify the clinical use case. The investigation into plasticity effects also adds valuable detail about real-world mechanical behavior. Clinically, the inclusion of a comparative table evaluating different force-limiting devices provides additional context for the role sliptures might play. The new anatomical testing (particularly regarding the florescence and pressure evaluations) and the implementation of the autonomous braking system are both well-integrated and useful additions that enhance the manuscript’s relevance to surgical practice.

I see no further issues that remain after the previous review round. The manuscript now reads clearly and is well-supported by experimental data and visualizations.

Response: We thank the referee for the constructive evaluation of our revised manuscript. We are pleased that the additional experiments and revisions are considered rigorous and that they have directly addressed the previous concerns.

Referee #5 (Remarks to the Author):

This paper presents a strategy for limiting the tensile forces applied during suture tying based on the inclusion of a slipknot in the suture thread, which ``slips out" at a preset tensile force. Applicable to robotic surgery, manual laparoscopic techniques, and open surgery, this approach addresses the need for repeatable force application when pulling on the suture thread to tie the surgical knots. Although it is nearly self-evident that there will exist a peak force during the opening of the slipknot, it is perhaps surprising that this force can be programmed reliably into the knot. This is a simple but compelling example of ``intelligent" behavior that results from purely mechanical action, without the need for electronic measurement and feedback control. As noted by the authors, many robotic surgery systems do not have the necessary functionality to sense the forces due to the additional design complexity, expense, and technical challenges of including them. The mechanics of the knot are clearly explained, and experimental data at multiple size scales soundly supports the technical conclusions. The approach is clever, low-cost, and initial experience reported here in both a human subjects experiment and an animal trial indicates that the sliputure technique may be a valuable operative technique once it is validated for specific surgical procedures. Since the opening of the slipknot can be detected visually, it is a promising technique for limiting force application during suturing in partially or fully automated surgical robotic systems.

The revisions have focused the article better on the core contribution of the work. The supplementary materials better explain the role of material plasticity in the mechanics and provide critical evidence about the reliability of the approach under varying environmental conditions (wet, dry, oiled, and over differences in the filament medium). Interestingly, direct tests clearly demonstrate that the performance is acceptable even when conditions vary from dry to saturated with simulated body fluids. Some models are now also provided to help understand the feasible force range, although it still seems likely that some amount of calibration for specific procedures will be needed in practice--which should be a solvable problem.

Response: We thank the referee for the positive and constructive evaluation. The mechanical model performs well in silicone and animal models; next we will calibrate and optimize sliputure performance in clinical settings to advance early translation.