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Citation

Marsidi, N., Vermeulen, S. A. M., Horeman, T., & Genders, R. E. (2020). Measuring forces in suture techniques for wound closure. *Journal Of Surgical Research*, *255*, 135-143. doi:10.1016/j.jss.2020.05.033

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Downloaded from:	https://hdl.handle.net/1887/3280077

Note: To cite this publication please use the final published version (if applicable).

JOURNAL OF SURGICAL RESEARCH • NOVEMBER 2020 (255) 135–143

Available online at www.sciencedirect.com

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Measuring Forces in Suture Techniques for Wound Closure

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ARTICLE INFO

Article history:
Received 12 December 2019
Received in revised form
27 March 2020
Accepted 3 May 2020
Available online 16 June 2020

Keywords:
Suture forces
Suture technique
Wound closure
Wound healing

ABSTRACT

Background: The use of sutures remains the first choice for wound closure. However, incorrect use of a suture technique can lead to impaired healing. Many techniques are described for high-tension wounds, but not much is known about their mechanical properties. Complications of excessive tension include dehiscence, infection, and ischemic necrosis and could be prevented. This study aimed to compare forces in five techniques (single, horizontal mattress, vertical mattress, pulley, and modified pulley suture) in a standardized wound tension model.

Materials and methods: A standardized neoprene wound model was developed on the ForceTRAP system (MediShield B.V., Delft, The Netherlands) to mimic a 5 Newton (N) wound. Five different suture techniques were each repeated 10 times by a student, resident dermatology, and dermsurgeon. The pulling force of the suture's first throw was measured with the Hook-in-Force sensor (Technical University Delft, The Netherlands). Changes in wound tension were measured by the ForceTRAP system. The ForceTRAP is a platform measuring forces from 0 to 20 N in three dimensions with an accuracy of 0.1 N. The Hook-in-Force is a force sensor measuring 0-15 N with an accuracy of 0.5 N. Maximum and mean forces were calculated for each suture technique and operator.

Results: Mean maximum pulling force: 5.69 N (standard deviation [SD], 0.88) single, 7.25 N (SD, 1.33) vertical mattress, 8.11 N (SD, 1.00) horizontal mattress, 3.46 N (SD, 0.61) pulley, and 4.52 N (SD, 0.67) modified pulley suture. The mean force increase on the skin (substitute) ranged between 0.80 N (pulley) and 0.96 N (vertical mattress).

Conclusions: The pulley suture requires less pulling force compared with other techniques. The mechanical properties of sutures should be taken in consideration when choosing a technique to close wounds.

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https://doi.org/10.1016/j.jss.2020.05.033

Introduction

It is indispensable for an optimal esthetic outcome after surgery to have proper knowledge of suture techniques and wound healing. Many factors have been described that influence wound healing to reduce excessive scar formation. External mechanical forces have been shown to have a strong influence on scar outcome.[1] These studies focus on tension-relieving techniques (e.g., layered subcutaneous sutures) or stress reduction.[2] Several studies show that postoperative management to decrease wound tension can lead to improved scar healing.[3] Another important, yet not often mentioned, factor is the skin closure technique. The skin closure technique is usually chosen depending on the location, size of the wound, and the surgeons' experience. Although numerous different techniques have been described,[4] very little is known about their mechanical influence.

Different factors in skin closure could influence the quality of scar healing. These include suture material design, suture material properties, suture technique, tissue handling, knot tying, controlling of tightening, and fluency in force profiles.[5] Mechanical strain plays an important role as incorrect wound tension may lead to impaired healing and pathologic scarring.[6] Especially in areas where wound tension is high after surgical excision, such as the scalp or lower leg, elaborate suture techniques are required for wound closure.[7] Single interrupted sutures are primarily used to close wounds but may hinder wound healing when used under high stress because of excessive tension on the wound edges. Other frequently used suture techniques in high-tension wounds are horizontal and vertical mattress and pulley sutures. The main advantage of using these techniques is that they allow the surgeon to close a defect with more ease if the tension on the skin is high. Another advantage specifically for a horizontal or vertical mattress is eversion of the wound edges, which could lead to a better esthetic outcome.[8] However, in all cases, pulling the knot too strong could compromise the vascularity in the wound edges.[9] Tension in the wound edges gives hemostasis, but complications can develop, including dehiscence, infection, and ischemic necrosis.[10] These complications are possibly a result of diminished blood flow caused by constriction of the tight suture.[11] In horizontal mattress sutures, the horizontal part of the thread can cut in the skin, causing it to become buried. This makes it difficult to remove and can give wound healing problems. Breakage of the suture thread could occur when too much force is applied on the suture because of improper technique. Another risk, especially in the fragile skin of elderly patients, is tearing of the thread through the skin.[12] For optimal wound healing, it is of importance to have knowledge of the properties of different suture techniques.

This study aimed to quantify and compare the pulling force of five different suture techniques (single interrupted, vertical mattress, horizontal mattress, pulley, and modified pulley) in a standardized wound tension model.

Materials and methods

Hardware

This study used two monitoring systems: the ForceTRAP system (MediShield B.V., Delft, The Netherlands) and the Hook-in-Force (HiF) (Technical University Delft, The Netherlands) shown in Figure 1. The ForceTRAP was developed as a visual feedback force measurement platform for training and assessment of surgical skills.[13] It is a validated platform and measures forces from 0 N to 20 N in three dimensions (X-axis, Y-axis, and Z-axis) with a sensitivity and accuracy of 0.1 and 0.5 N, respectively. The HiF sensor is a validated sensor and designed as a force sensor for pulling forces in sutures.[14] It has a working range of 0-15 N with an accuracy of 0.5 N and a sensitivity of 0.1 N. This sensor enables to measure the amount of force needed in the strand to close the wound (the other strand is fixated). A setup was made with a modification of the ForceTRAP to mimic a wound with intrinsic tension. For good comparison, the initial tension and distribution of the force over the skin sample should be constant. Therefore, the skin sample is mounted in 2 bars that distribute the force along the hole side of the skin sample (Fig. 2). The first bar is directly connected to the ForceTRAP, and the second bar connects the skin sample to the common ground of the setup. Between the first bar and the base of the setup, an adjustment module was placed that allows the researcher to adjust the force acting on the sample to $5\ N \pm 0.1$ to resemble a high-tension wound. This force level, which mimics a high-tension wound, was found in a recently described experiment from the literature.[15]

Neoprene was chosen as a suitable skin replacement and could withstand the high forces in the sutures. A standardized method was developed to ensure minimal differences in the artificial skin samples. The neoprene pad was laser cut in 9.5×9.5 cm squares and 3.5 mm in thickness. A length defect of 2 cm was chosen that resembles a common elliptical excision (the length corresponds with three times the diameter of a lesion) mostly used to excise nevi or small skin tumors.[16] With a 30° wound edge angle, the width was 3.14 mm. With the ForceTRAP, a standard force of 5 N was set on the wound pad. This standardized setup enabled us to close the wound in the middle with a single suture for each technique (Fig. 2). The same force needed to close the gap was guaranteed by using a fixed defect with a fixed tension.

Software

Two separate computers were used to measure the ForceTRAP and HiF. Two user interfaces were built (Technical University Delft) in MATLAB (MathWorks, Natick, MA) to record and display the output from the ForceTRAP and HIF sensor. The ForceTRAP interface shows forces in a three-dimensional plane and three different two-dimensional planes, whereas the HiF shows the pulling force in diagram 1 degree of freedom graph only. Each user interface runs on an independent platform and stored data in Matlab or excel with a minimum frequency of 30 Hz. Visualization of the force is used only to

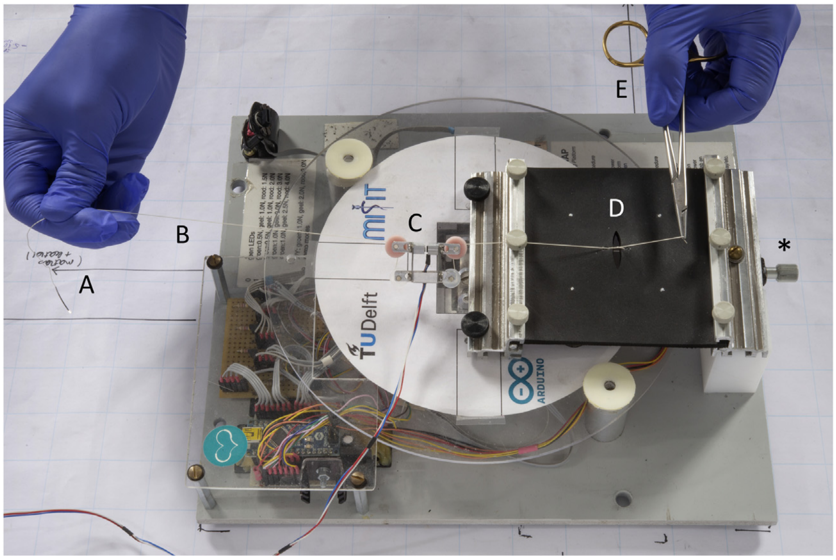

Fig. 1 – Suture task setup. (*) A neoprene pad is set to 5 N. (A and B) Arrows on the place mat show the direction of the pulling hand and suture. (C) The HIF is set in between the suture and the pulling hand to measure the maximum force. (D) The suture technique is set in place. (E) The other hand fixates the suture and does not apply additional force. (Color version of figure is available online.)

check the systems during the experiments by the researcher and does not influence the measurements itself.

Experimental setup

The ForceTRAP setup was placed on a white place mat on a table in front of the sitting participant. On this place mat, arrows were drawn showing the pulling directions of the suture. As the seat location was fixed behind the setup, the posture and location of the participant arms were standardized as good as practically possible. The experiments were conducted by two persons: one performing the suture task and one controlling the computers and to ensure that the suture movements were performed correctly.

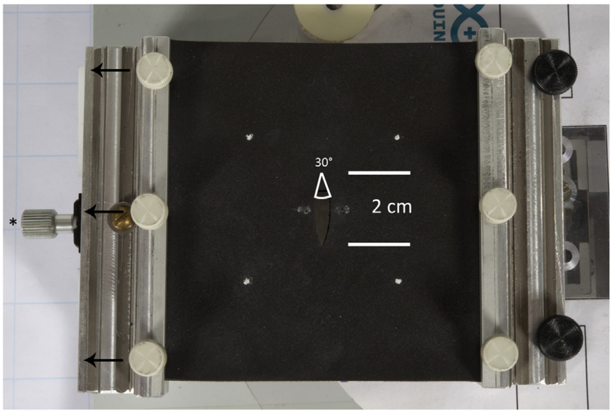

Fig. 2 – A neoprene pad is laser cut in a 2 cm wound with 30° angles. It is then mounted in the ForceTRAP with rigid bars on all four corners. On one side, a traction system (*) can apply force on the wound. (Color version of figure is available online.)

Test protocol

A standardized test protocol was conducted by each participant. First, the neoprene skin pad was mounted and secured in the bars of the ForceTRAP setup. Second, a 5 N force was applied to the neoprene skin pad (observed by the ForceTRAP software) by means of the force adjusting system between the second bar and mounting frame (Fig. 1: *). Third, the measurements were started on both laptops so that both HiF and ForceTRAP software programs were running simultaneously. Fourth, the measurement started, and a suture was made using one of the five suture techniques (Fig. 1D). The HiF was secured on the strand between the suture and the pulling hand (Fig. 1A-C). The other strand of the suture was fixated using a needle holder (Fig. 1E). After the wound edges touched (the wound was then considered closed), the suture task was completed and the measurements were stopped. Finally, the suture knot was released, and the ForceTRAP pretension was readjusted to 5 N before the process was repeated, and a new suture was made. Each suture technique was repeated 10 times with a new suture and skin pad. The experiments were conducted by a medical student, resident dermatology, and expert (dermsurgeon).

Suture techniques

Five different suture techniques were chosen. An Ethilon 3.0 monofilament nylon suture (Ethicon, Inc, NJ) was used for every technique. The *single interrupted suture* inserts in the center of the wound and 4 mm from the wound edge. It exits 4 mm on the opposite side. The *vertical mattress suture* (far-far-

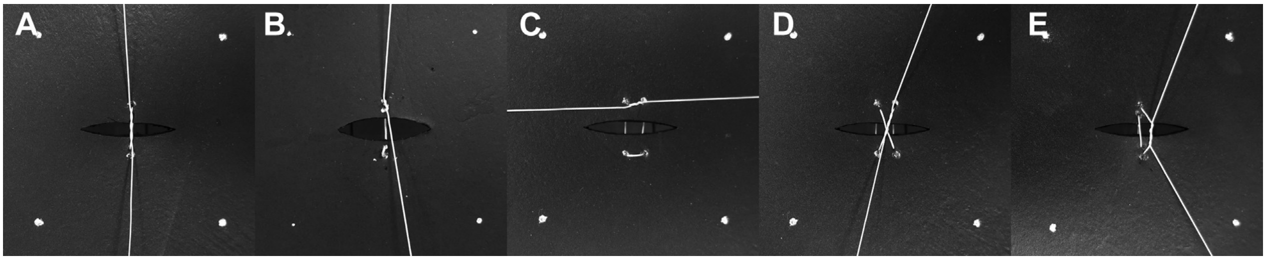

Fig. 3 – Suture techniques. A = single, B = vertical mattress, C = horizontal mattress, D = modified pulley, and E = pulley.

near-near system) inserts in the center of the wound 4 mm from the wound edge. It exits 4 mm on the opposite side. It is then reinserted 2 mm from the edge. It exits 2 mm from the edge on the starting side. The *horizontal mattress suture* inserts 4 mm from the wound edge and 2 mm below the center of the wound. It exits 4 mm from the wound edge, 2 mm below the center of the opposite side. It is reinserted 4 mm from the edge and 2 mm above the center. It exits 4 mm from the edge and 2 mm above the center on the starting side. The *pulley suture* (far-near-near-far system) inserts 4 mm from the edge and exits 2 mm from the edge on the opposite side. It is reinserted 2 mm from the edge on the starting side and exits 4 mm from the edge on the opposite side. The *modified pulley suture* inserts 4 mm from the edge and 2 mm above the center. It exits in the same spot on the opposite side. It is reinserted 4 mm from the edge and 2 mm below the center. It then exits in the same spot on the opposite side (crossed knotted). The templates are shown in Figure 3.

Statistical analyses

From the HIF sensor force data, the parameters maximal force, mean force, and standard deviation (SD) were calculated. From the ForceTRAP force data, the maximum and mean force increase and SD were measured. The differences in parameter outcomes between suture types were analyzed using an analysis of variance test. Statistical analysis was performed using SPSS statistics (version 23.0; IBM Corp, Armonk, NY). Differences were considered statistically significant if $P < 0.05$.

An institutional review board or local ethics committee approval was not applicable for this study.

Table 1 – Mean maximum force for the five suture patterns required to close a 2 cm elliptical wound with 5 N intrinsic tension.

Technique	Force in Newton (SD)
Single interrupted	5.69 (0.88)
Vertical mattress	7.25 (1.33)
Horizontal mattress	8.11 (1.00)
Modified pulley	4.52 (0.67)
Pulley	3.46 (0.61)

Results

A total of 30 experiments were conducted for each suture technique by three different participants (student, resident, and expert). None of the sutures or skin pads broke or tore.

HiF (pulling force)

The highest maximum force measured in the HiF was 10.7 N in the horizontal mattress suture. The maximum force in the other sutures was 10.5 N (vertical mattress), 8.12 N (single interrupted), 6.1 N (modified pulley), and 5.3 N (pulley). The mean maximum force (i.e., 30 repeats by three users) measured by the HiF sensor was 5.69 N (SD, 0.88) for the single interrupted, 7.25 N (SD, 1.33) for the vertical mattress, 8.11 N (SD, 1.00) for the horizontal mattress, 3.46 N (SD, 0.61) for the pulley, and 4.52 N (SD, 0.67) for the modified pulley suture (Table 1). The one-way analysis of variance test showed a significant difference between the single interrupted, vertical and horizontal mattress, pulley, and modified pulley sutures (Table 2; $P < 0.05$).

Analyses per participant indicate that the order for highest to lowest score of the averaged maximum HIF was similar for each participant: horizontal mattress, vertical mattress, single, modified pulley, and pulley (Fig. 4). However, each participant showed statistical differences between the techniques (Table 3). The medical student did not show a

Table 2 – One-way analysis of variance results of combined experiments ($n = 30$ per technique).

Suture techniques	Mean difference (in Newton)
Vertical-single	1.58
Horizontal-single	2.42
Single-modified pulley	1.18
Single-pulley	2.23
Horizontal-vertical	0.86
Vertical-modified pulley	2.73
Vertical-pulley	3.79
Horizontal-modified pulley	3.60
Modified pulley-pulley	1.05
Horizontal-pulley	3.60

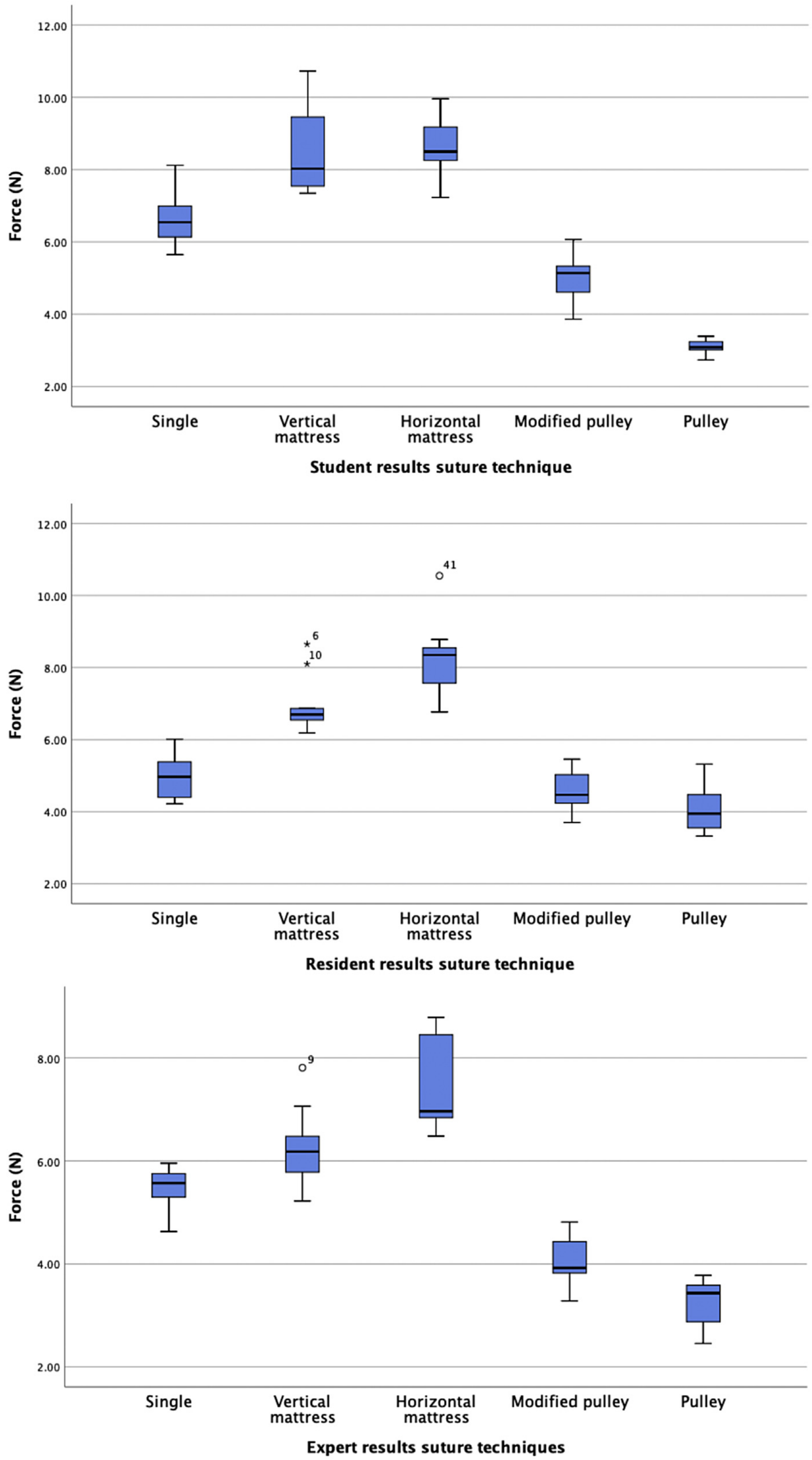

Fig. 4 – Boxplots of the pulling force per participant. N = newton. (Color version of figure is available online.)

significant difference between the horizontal and vertical mattress. The resident dermatology did not show a significant difference between the modified pulley *versus* single, pulley *versus* single, and modified pulley *versus* pulley. The expert dermatologist did not show a significant difference between the single *versus* vertical mattress suture.

Table 3 – HiF analysis of variance results per experience level. Non-significance is indicated with P-value above the P = 0.05 significance level.

Suture techniques	Student	Resident	Expert
Vertical-single	1.93	1.97	**0.76 (P = 0.55)**
Horizontal-single	2.01	3.28	1.97
Single-modified pulley	1.67	**0.43 (P = 0.68)**	1.42
Single-pulley	3.52	**0.93 (P = 0.056)**	2.23
Horizontal-vertical	**0.08 (P = 0.99)**	1.31	1.20
Vertical-modified pulley	3.60	2.41	2.19
Vertical-pulley	5.45	2.90	3.00
Horizontal-modified pulley	3.68	3.7	3.40
Modified pulley-pulley	1.85	**0.49 (P = 0.58)**	0.81
Horizontal-pulley	5.53	4.21	4.21

The analysis of variance results show the mean difference between the suture techniques (first technique minus second technique in Newton).

ForceTRAP (force increase)

The initial starting force applied with the ForceTRAP on the standardized neoprene skin was 5.00 N (SD, 0.06). The mean force increase had a range between 0.80 N (pulley) and 0.96 N (vertical mattress) (Fig. 5). A significant difference could not be found between the groups.

Analyses per participant in indicate significant differences between the techniques for all categories with the exception for the medical student. The resident showed a significant difference between the vertical mattress and all other suture techniques. The expert showed a significant difference between the single suture *versus* modified and normal pulley and between the horizontal mattress and pulley.

Discussion

This study shows that the pulley technique uses the least amount of pulling force when tying the first knot. Second is the modified pulley, followed by the single interrupted, vertical mattress, and horizontal mattress.

Not many experiments have been done comparing suture techniques for cutaneous defects although they are one of the most fundamental skills in surgery, taught to medical students and residents. The currently available studies focus primarily on the force acting on the skin when closing a wound.[17,18] These results, however, do not provide information on the effect of the suture techniques on the strain/tension forces of the wound edges. By measuring the pulling force

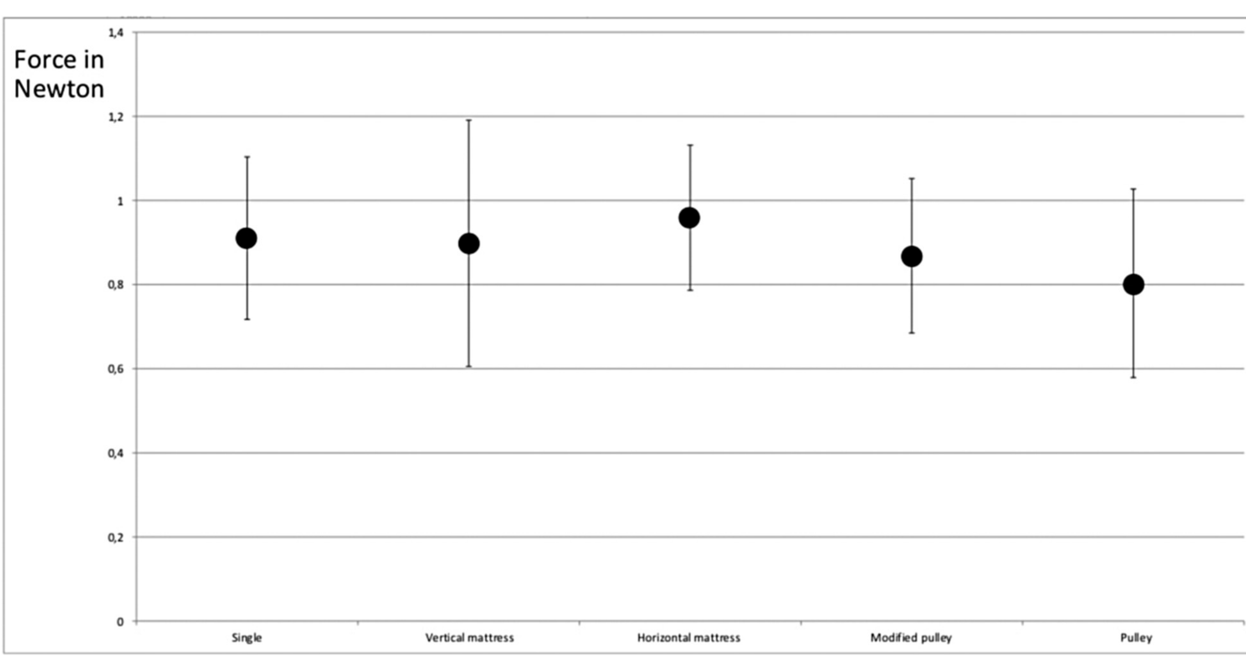

Fig. 5 – Force increase as measured by the ForceTRAP with SD.

that is needed to knot a suture, we can identify the force in the wound edges.

One study by Austin and Henderson[19] compared four different suture patterns (simple interrupted, modified pulley, horizontal mattress, and double butterfly) using a different setup. A suture pattern threaded through a series of parallel rings mimicked a wound. One end of the suture was attached to a fixed tensiometer, whereas the other end was attached to a free tensiometer. This setup enabled them to measure the maximum pulling force needed to draw the rings closer. They concluded that the pulley suture required the least maximum pulling force (0.34 kg ± 0.08) to close a distance of 3.81 cm. The advantage of a pulley suture is because of its mechanism: multiple wheel pulleys distribute forces for more than one parallel segment. Mattress sutures also use multiple loops, but their segments are nonparallel and therefore less efficient. The study by Austin and Henderson and our study found comparable results, but our *ex vivo* model may be regarded as a more realistic setup. Instead of using a tensiometer, we used participants to perform the test sequences. This difference is crucial as technical skills, such as hand placement, positioning, and instrument handling, can affect the amount of force as in real-time surgery. These variations can be seen in our results as there are differences in the individual analysis of both the HiF and ForceTRAP. This especially accounts for the ForceTRAP for which we expected no differences as the distance between the wound edges was the same for every technique. Individual analysis clearly showed differences between the resident and expert. This variation in wound closure displacement is not entirely understood. One explanation could be that it is caused by using a slightly different angle of the hand, which gives more pressure on the Z-axis and is added to the X-axis and Y-axis. Another explanation could be the fluency of the hand motion. We found that each knotted suture has its unique curvature when plotted in a graph. Although this study did not focus on this subject, the example in Figure 6 shows how 10 attempts of a singe subject placing a pully suture can deviate frome achother. As having multiple pulleys is a benefit for a smooth hand motion, having nonparallel segments, such as the mattress suture, could be a disadvantage for the hand motion and give more friction in the knot and thread. Our setup was not suitable to perform statistical analysis for this, and future studies are needed to support this hypothesis.

Although all suture techniques have been described to close wounds under tension, this indicates that the pulley suture and its variants are favorable to reduce the amount of wound edge tension, which could enhance wound healing. Other benefits described for the pulley suture are a fast and a cost-effective technique[20] and as an alternative for flap reconstruction in large-scalp defects (>3 cm),[21] which often occur in skin cancer surgery.

Our data show that the single suture technique uses less pulling force than both mattress sutures, but in clinical use, a mattress suture is far easier to perform for large defects despite the measured high pulling force. The high pulling force however could cause a diminished blood flow in the wound edges.

A noticeable result of our experiment is that, although the level of experience between the participants varies, they all have the same highest to lowest rank of suture technique. This could suggest that experience is not a requirement to

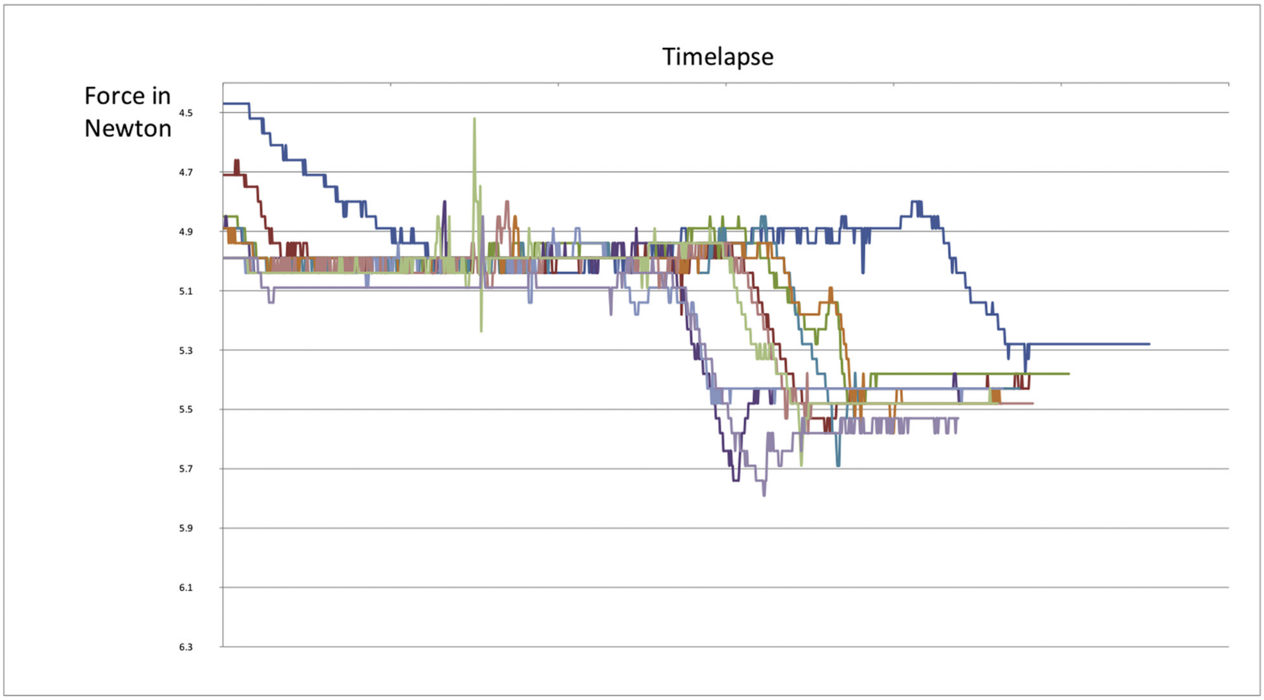

Fig. 6 – Example of the force measured with ForceTRAP in time. Conducted by the medical student performing the pulley suture technique. (Color version of figure is available online.)

apply less force that is in a pulley suture than in a horizontal mattress suture. However, as the number of participants participated in this study is low, it is suggested to expand the study population to validate this hypothesis.

Limitations

Although neoprene was chosen for its homogeneity and property consistency being very beneficial for good comparison between sutures, it was not the ideal representative for real skin. Neoprene skin pad does not have the same properties as actual skin, and there could be some differences in friction of the thread and behavior of the material. The results however show an equal amount of pulling force needed in every newly conducted suture and are considered reliable. Another limitation could be the number of repetitions per suture technique that was used to analyze the pulling force (10 times per technique). In a preliminary study (conducted by S.A.M.V.), we compared the pulling forces when applied 30 times *versus* 10 times and found no significant difference.

For consistency reasons, we only used one type of suture type and material in our study (Ethilon). It is possible that other suture types and brands can influence the results because of the different characteristics of the thread type (i.e., monofilament or multifilament) and materials. For example, it is expected that multifilament sutures will have more friction than monofilament sutures. Therefore, it is expected that the thread type or material has influence on the absolute HIF levels. However, in a comparison study, it is not expected that the thread type or material influences the HIF ranking of different suture techniques as found in this study.

This study shows clear differences in suture techniques. But there is still much to learn about the forces that are used during suturing and in the sutures themselves. We hope that our study contributes in choosing the appropriate suture technique and that it will stimulate future research.

Conclusion

Our study indicates that the pulley and modified pulley suture requires less amount of pulling force when tying a knot and could be more favorable compared with a single interrupted vertical mattress or horizontal mattress suture in high-tension wounds. Which surgical technique will be used usually depends on the size of the wound, anatomic location, and experience of the surgeon. Having knowledge of the mechanical properties of suture techniques could enhance wound healing, and esthetic outcome as the least damaging technique should be used to close or approximate wounds.

Acknowledgment

The authors thank Jerry van der Ploeg and Huybert van de Stadt (R&D Department, Leiden University Medical Center) for making the changes to the ForceTRAP and traction system.

Authors' contributions: N.M. and T.H.: Conceived and designed the experiments: N.M., S.A.M.V., and R.E.G.: Performed the experiments. N.M., S.A.M.V., and T.H.: Analyzed the data. T.H.: Contributed reagents/materials/analysis tools. N.M., T.H., and R.E.G.: Wrote the manuscript.

Disclosure

Tim Horeman is founder of MediShield B.V., a Technical University Delft MedTech startup but did not receive any financial support for this research. The authors have no conflict of interest to disclose.

REFERENCES

1. Bush JA, McGrouther DA, Young VL, et al. Recommendations on clinical proof of efficacy for potential scar prevention and reduction therapies. *Wound Repair Regen*. 2011;19(suppl 1):s32–s37.
2. Gurtner GC, Dauskardt RH, Wong VW, et al. Improving cutaneous scar formation by controlling the mechanical environment: large animal and phase I studies. *Ann Surg*. 2011;254:217–225.
3. Barnes LA, Marshall CD, Leavitt T, et al. Mechanical forces in cutaneous wound healing: emerging therapies to minimize scar formation. *Adv Wound Care (New Rochelle)*. 2018;7:47–56.
4. Adams B, Levy R, Rademaker EE, Goldberg LH, Alam M. Frequency of use of suturing and repair techniques preferred by dermatologic surgeons. *Dermatol Surg*. 2006;32:682–689.
5. Rodrigues SP, Horeman T, Dankelman J, van den Dobbelsteen JJ, Jansen FW. Tying different knots: what forces do we use? *Surg Endosc*. 2015;29:1982–1989.
6. Son D, Harijan A. Overview of surgical scar prevention and management. *J Korean Med Sci*. 2014;29:751–757.
7. Regula CG, Yag-Howard C. Suture products and techniques: what to use, where, and why. *Dermatol Surg*. 2015;41(suppl 10):S187–S200.
8. Moody BR, McCarthy JE, Linder J, Hruza GJ, et al. Enhanced cosmetic outcome with running horizontal mattress sutures. *Dermatol Surg*. 2005;31:1313–1316.
9. Zuber TJ. The mattress sutures: vertical, horizontal, and corner stitch. *Am Fam Physician*. 2002;66:2231–2236.
10. Yazdani Abyaneh MA, Levitt JO. Understanding the logic of common suturing techniques in dermatologic surgery. *Dermatol Online J*. 2015;21.
11. Sagi HC, Papp S, Dipasquale T. The effect of suture pattern and tension on cutaneous blood flow as assessed by laser Doppler flowmetry in a pig model. *J Orthop Trauma*. 2008;22:171–175.
12. Burkhardt R, Preiss A, Joss A, Lang NP. Influence of suture tension to the tearing characteristics of the soft tissues: an in vitro experiment. *Clin Oral Implants Res*. 2008;19:314–319.
13. Horeman T, Blikkendaal MD, Feng D, et al. Visual force feedback improves knot-tying security. *J Surg Educ*. 2014;71:133–141.
14. Horeman T, Meijer EJ, Harlaar JJ, Lange JF, van den Dobbelsteen JJ, Dankelman J. Force sensing in surgical sutures. *PLoS One*. 2013;8:e84466.
15. Paul SP, Matulich J, Charlton N. A new skin tensiometer device: computational analyses to understand biodynamic excisional skin tension lines. *Sci Rep*. 2016;6:30117.
16. Reddy KK, Farber MJ, Bhawan J, Geronemus RG, Rogers GS. Atypical (dysplastic) nevi: outcomes of surgical excision and

association with melanoma. *JAMA Dermatol*. 2013;149:928–934.
17. Melis P, Noorlander ML, Bos KE. Tension decrease during skin stretching in undermined versus not undermined skin: an experimental study in piglets. *Plast Reconstr Surg*. 2001;107:1201–1205. discussion 1206-7.
18. Capek L, Jacquet E, Dzan L, Simunek A. The analysis of forces needed for the suturing of elliptical skin wounds. *Med Biol Eng Comput*. 2012;50:193–198.
19. Austin BR, Henderson RA. Buried tension sutures: force-tension comparisons of pulley, double butterfly, mattress, and simple interrupted suture patterns. *Vet Surg*. 2006;35:43–48.
20. Kannan S, Mehta D, Ozog D. Scalp closures with pulley sutures reduce time and cost compared to traditional layered technique—a prospective, randomized, observer-blinded study. *Dermatol Surg*. 2016;42:1248–1255.
21. Malone CH, McLaughlin JM, Ross LS, Phillips LG, Wagner Jr RF. Progressive tightening of pulley sutures for primary repair of large scalp wounds. *Plast Reconstr Surg Glob Open*. 2017;5:e1592.