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Technical note

Resistance forces acting on suture needles

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Abstract

Understanding the resistance forces encountered by a suture needle during tissue penetration is important for the development of robotic surgical devices and virtual reality surgical simulators. Tensile forces applied to skin and tendon during suturing were measured. Fresh sheep achilles tendons were tensioned with a static load 4.9 N, 9.8 N or 19.6 N and sheepskin with 0.98 N, 2.9 N or 4.9 N static load. A straight 2/0 cutting suture needle in series with a load cell on a materials testing machine penetrated the tissue at 90° with a velocity of 1, 5 or 10 mm/s for each tissue tension ($n = 5$). Continuous load versus displacement data was obtained and penetration load and stiffness were noted. The load versus displacement curve for skin during needle penetration demonstrated two characteristic peaks, corresponding to initial penetration and emergence of needle from the undersurface of the tissue. Increasing the tension within the tissue (skin and tendon) increased the amount of force required to penetrate the tissue with a suture needle ($p < 0.05$). Needle displacement rate did not affect the resistance to needle penetration ($p < 0.05$). This study provides a simple model for measuring force-feedback during needle penetration of soft tissues and is a good starting point for future studies of the penetration resistance properties of human tissues.

Keywords: Suture needle; Force; Penetration; Soft tissues; Mechanical properties

1. Introduction

Virtual reality (VR) surgical simulators are an effective educational tool (Rosen et al., 1999). Current computer generated imaging closely models the visual surgical environment, but realistic tactile and force (haptic) feedback is lacking. Improving the haptic feedback through accurate characterization of the mechanical properties of soft tissues enhances the realism and educational benefit of surgical simulators. The integration of robotic technology into the surgical environment requires accurate mathematical modelling based on mechanical testing of soft tissues (Miller and Chinzei, 1997).

The use of needles during suturing is one of the most common procedures in surgery. Previous studies have evaluated suture needle penetration, examining the effect of needle material properties and geometry on function (Towler et al., 1988; McClung et al., 1992; Edlich et al., 1990; Bendel et al., 1986). These studies focused on the mechanical properties of the needle rather than the tissue. The tissue response to loading constitutes the haptic feedback to the surgeon during suturing. In order to develop a surgical simulator with haptic fidelity, the tissue response to needle penetration forces must be characterized. This study examined the resistance forces encountered during the passage of a straight suture needle through sheepskin and sheep tendon to provide input data for haptic VR surgical simulation.

2. Method

Ethics approval was obtained for the acquisition and use of animal tissue in this study.

2.1. Determination of tissue tension

The axial load applied to the free wound edges of sheepskin and tendon were determined so that realistic axial loads could be placed on the tissue during subsequent testing. Two experienced surgeons were asked to place a suture through the free edge of

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sheepskin (4 cm by 10 cm sections) harvested from the back and achilles tendon samples harvested from the hindlimbs. The surgeons provided the necessary force on the free edge of skin or tendon by pulling on a spring scale with their retracting hand (Salter Abbey precision spring balance, Salter Abbey Weighing Machines, England) (Fig. 1). The load required to pull the tissue to correct tension during suturing was recorded, varying between 1.5 and 2.5 N (mean 1.9 N) for skin and between 4.9 and 5.9 N (mean 5.4 N) for tendon.

2.2. Sheepskin

Three adjacent rectangular patches of lumbar skin from a two-year-old cross bred wethers sheep (4 cm wide by 10 cm long) were harvested. The 4 cm edge of the skin was stitched to thin metal rods. A jig to hold tissue with a static uniaxial load (0.98, 2.9, 4.9 N) was used across the 4 cm stitched skin sample (Fig. 2).

The jig assembly was positioned on an MTS 858 Mini Bionix material testing machine (MTS, Minnesota, USA) (Fig. 2). A straight cutting suture needle (Silkam USP 2/O natural silk, B Braun Surgical, Melsungen, Germany) was attached in series with a load cell on the actuator. The needle has an equilateral triangular cross-section with a height of 0.88 mm and an area of 0.77 mm^2 (Fig. 2a). The needle was passed at constant displacement rate through the skin and load vs. displacement data recorded on a personal computer. Three needle velocities (1, 5, and 10 mm/s) were tested at three axial loads (0.98, 2.9, 4.9 N) with five test samples per group. This process of 45 punctures was repeated for three adjacent skin samples. A fresh needle was used for each sample of skin and the order of tension and displacement rate combinations was varied between each skin sample.

2.3. Sheep tendon

Achilles tendons were mounted in the jig assembly in the same manner as the skin samples with a total length of 10 cm. The jig was placed in the MTS machine and tested at needle velocities of 1, 5, and 10 mm/s under axial loads of 4.9, 9,8, 19.6 N on each of three tendons with five test samples per group. The order of axial load and velocity combinations was varied between each tendon and a fresh needle was used for each tendon.

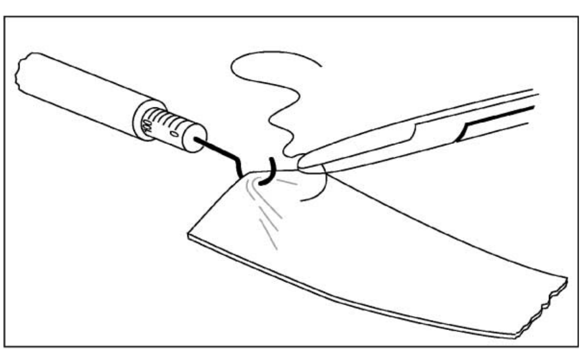

Fig. 1. Axial force used during suturing measured on a spring scale.

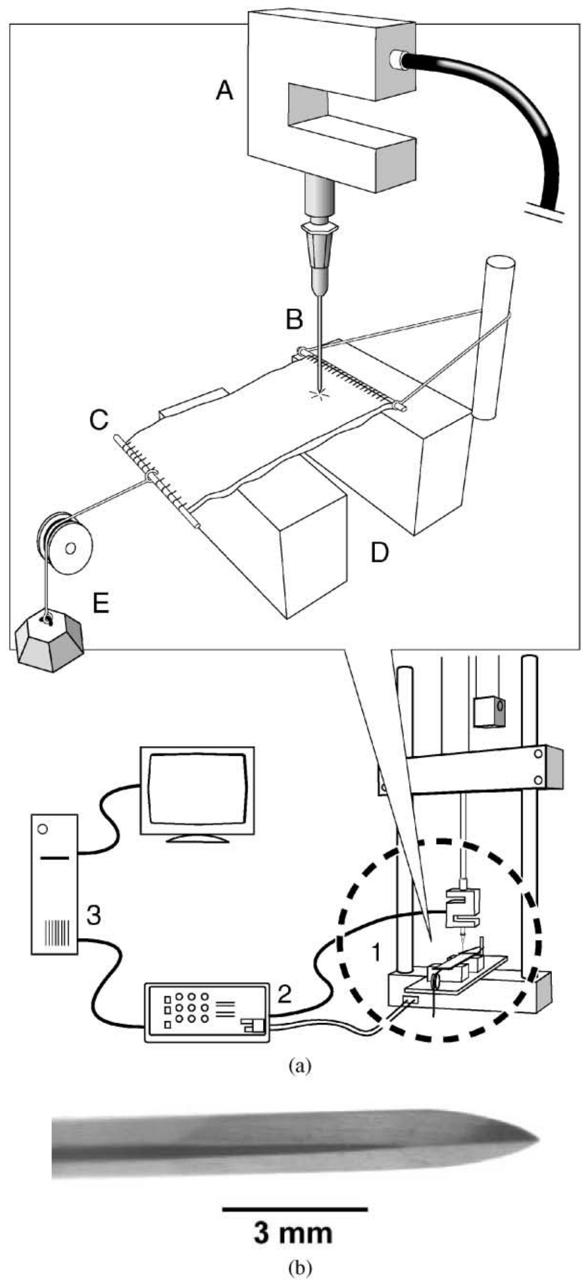

Fig. 2. (a) Jig assembly for measurement of resistance forces during needle penetration of tissue. 1—Tissue under known axial load being penetrated by suture needle on a material testing system (MTS) machine. A—Load cell, B—needle, C—skin Sample, D—supports, E—tensioning Mass. 2—MTS controller. 3—Personal computer. (b) Image of the needle tip used in the experimental testing.

2.4. Force data

A typical load vs. displacement curve during needle penetration of skin is shown in Fig. 3. The curve

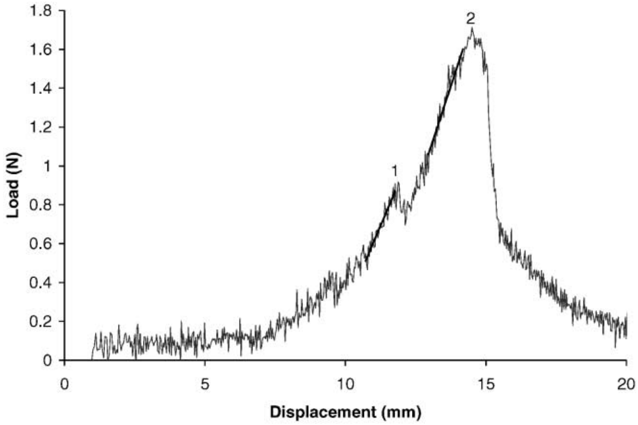

Fig. 3. Load vs. displacement curve for sheepskin under a tensile load of 2.9 N. Needle velocity was 5 mm/s. Peaks are present at the point of needle penetration of the epidermis (1) and needle emergence from the skin undersurface (2). The slope regions where the pre-penetration and pre-terminal slopes (N/mm) were assessed preceded these peaks.

characteristically demonstrates two peaks. The slope of the curve prior to the first peak (pre-penetration slope), the slope of the curve prior to the second peak (terminal slope) and the load at which the fist peak occurred were noted. Data were analyzed using an analysis of variance and a post-hoc Tukey Honest Significant Difference test where appropriate (Statistica, Statsoft, Tulsa, OK, USA).

3. Results

Greater axial force was required by the surgeons during needle passage through tendon (mean 5.3 N) than through skin (mean 1.9).

3.1. Skin

The load vs. displacement curve during needle penetration of sheepskin demonstrated two peaks in 90% of tests. The first peak occurred during the puncture of the skin, and did not vary significantly with needle velocity or axial force ($p > 0.1$) (Fig. 4). The slope of the load vs. displacement curve just prior to penetration of the skin by the needle was not affected by needle velocity, but increased with increasing axial force (Fig. 5).

The second, higher peak corresponded to the emergence of the needle from the under surface of the skin. The slope of the load vs. displacement curve prior to this peak corresponded to the resistance offered to the suture needle as it passed through the skin tissue. As with the pre-perforation stiffness, the stiffness of the curve in the pre-terminal region did not vary significantly with needle velocity, but increased with increasing axial force (Fig. 6).

3.2. Tendon

The load vs. displacement curves for tendon demonstrated one peak (Fig. 7). The slope of the load vs. displacement curve increased slightly with increasing needle velocity but this was not significant (Fig. 8) and increased significantly with increasing axial load within the tendon (Fig. 9).

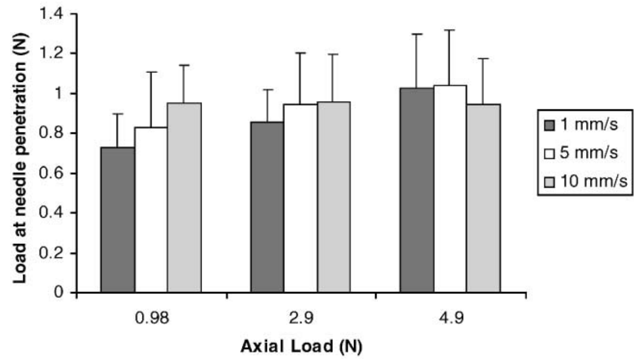

Fig. 4. Effect of needle velocity and axial load on force required to penetrate skin epidermis (mean + SD).

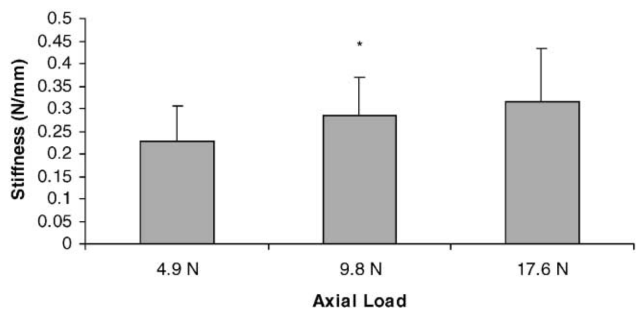

Fig. 5. Effect of axial load on the pre-penetration slope of load vs. displacement curve (mean + SD, *$p < 0.05$).

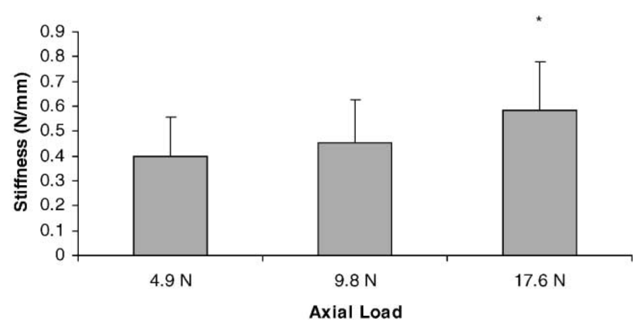

Fig. 6. Effect of axial load on the pre-terminal slope of load vs. displacement curve (mean + SD, *$p < 0.05$).

4. Discussion

The development of virtual reality techniques and the emergence of automated surgical tools and robots has prompted research into the computer simulation of surgical procedures (Miller et al., 2000). Computer simulations rely on experimental data for their accuracy

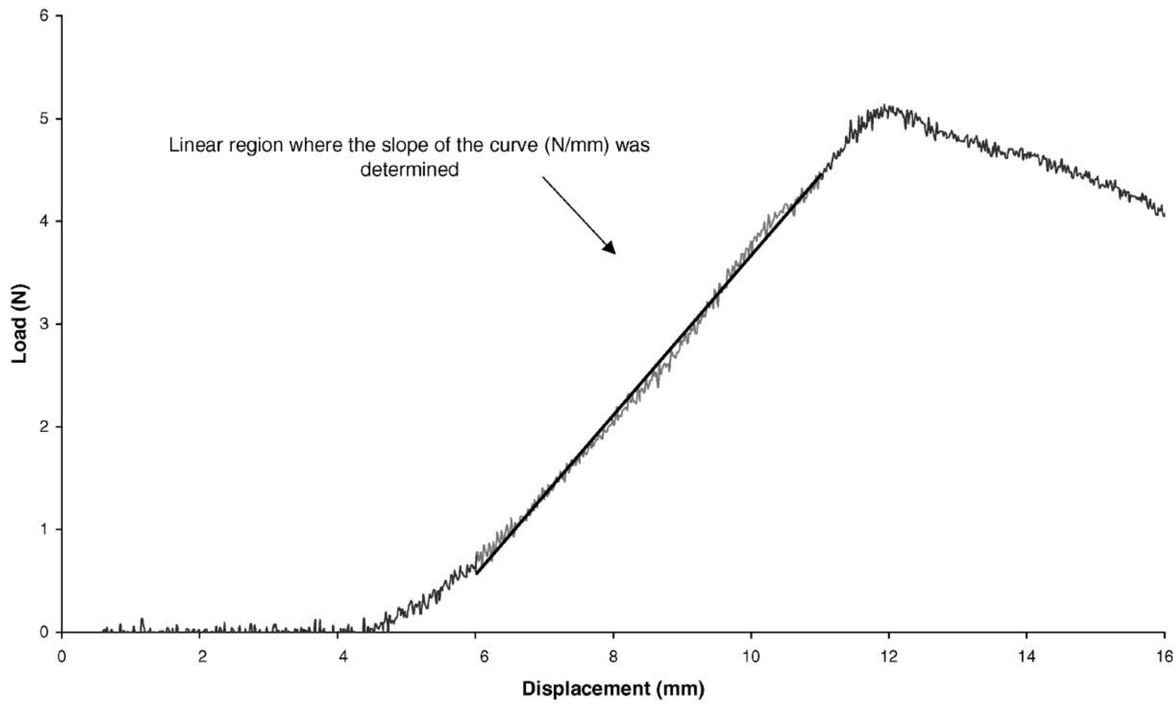

Fig. 7. Load vs. displacement curve for sheep tendon with a needle velocity of 1 mm/sec. The only peak is at the point of needle emergence from the undersurface.

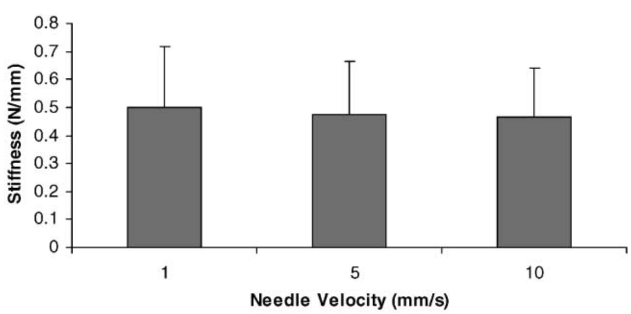

Fig. 8. Effect of needle velocity on the stiffness (N/mm) during tendon penetration (mean + SD).

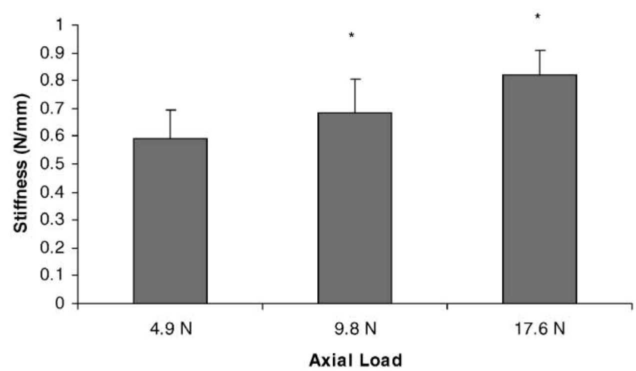

Fig. 9. Effect of axial load on the stiffness (N/mm) during tendon penetration (mean + SD, *$p<0.05$).

due to the high degree of variability between both types of tissue and individuals. The passage of a suture needle through soft tissue is important in VR surgical modelling of tissue behavior because it is a fundamental action in most surgical procedures (i.e. tendon repair, skin closure). This study examined the resistance forces during suturing in two types of tissues commonly sutured in surgical procedures. Tendon and skin represent test specimens of a predominately parallel and randomly arranged matrix, respectively.

Previous mechanical studies of suture needles have concentrated on the effect of needle design. Needle sharpness has been evaluated in terms of the maximum forces required to penetrate synthetic membranes or porcine cornea (McClung et al., 1992, Edlich et al., 1990) and other properties specific to the needle have been studied, such as bend strength and ductility (Bendel et al., 1986). Cutting tip geometry was important for ease of tissue penetration (Towler et al., 1988; Edlich et al., 1993). These studies, however, did not examine the load-displacement curves or its material-dependent characteristics, such as stiffness. The rate of needle penetration as well as axial load within the tissue or synthetic membrane penetrated were not examined as variables.

Skin and other tissues, in vivo, are subject to biaxial tension, which not only keeps them in their proper form but also offers resistance to deformation, particularly in tension. During suturing, the surgeon applies an axial load to the free edge of the wound to stabilize it prior to placement of the suture needle. In this study, the surgeons applied less tensile force to skin compared to tendon during suturing. This may reflect differences in the mechanical properties of the tissues and the feedback to the surgeon. Applied force had a significant effect on the resistance to needle penetration (Figs. 5, 6 and 9). This study applied an axial load to stabilize the tissues as the surgeon would during suturing. The axial forces applied to tissue edges during suturing need to be considered to offer an accurate assessment of the resistance encountered by suture needles during tissue puncture. These forces were measured and the uniaxial load was controlled for each sample tested in our study.

4.1. Skin

Skin is composed of two main layers: the outer epidermis and inner dermis (Ankersen et al., 1999). Most of the material strength of skin is provided by the dermis, which is made up of densely packed collagen fibers at random orientations, elastin fibers, and a ground substance. This dual-layered structure causes skin to be supple at low strain but to exhibit considerable stiffness at higher strains. The outer epidermis is punctured at the first peak and the second, higher peak is generated as the dermis, which provides most of the strength of skin, is pierced. The characteristic two-peaked curves generated agree with data from other skin puncture studies involving the mechanics of knife stabbing (O'Callaghan et al., 1999; Ankersen et al., 1999). Neither O'Callaghan nor Ankersen commented on the multiple peaks that appeared in their data. These two peaks and the stiffness slopes that accompany them are of particular interest in the design of a virtual reality surgical simulator. Differences in stiffness and strength that give each type of tissue its unique "feel" need to be considered in surgical simulators. Brett et al. (1997) reported two peaks during hollow needle penetration into the epidural space corresponding to the supraspinous ligament and ligamentum flavum, but did not comment on peaks occurring during skin penetration.

Increasing the axial load to the skin during suturing increased the force required to puncture the tissue. Increasing the axial force decreased the bending as the tissue becomes more rigid with increasing force, thereby improving the surgeon's control of the tissue. The slope of the load vs. displacement curve of the penetrating needle increased with increasing axial force (Figs. 5 and 6).

4.2. Tendon

Tendon is largely made up of collagen fibers in a linear array. The load vs. displacement curve during needle penetration demonstrated a single peak, which occurred when the needle emerged from the undersurface of the tissue (Fig. 7). There was no peak when the needle first penetrated the tissue. This may be due to the needle separating rather than penetrating the linear fiber bundles. As with skin, increasing the axial force increased the slope of the load vs. displacement curve during needle penetration (Fig. 9). There was an increase in the slope of the load vs. displacement curve during needle penetration with increasing needle velocity, but this was not statistically significant (Fig. 8). Differences between mean values were small and would require a large sample size to delineate any difference. The power of this study into the effect of displacement rate was small (0.1–0.5), and an increased sample size may result in a significant result.

4.3. Needle velocity

Brett et al. (1997) used a tensile testing machine to map the resistance force to hollow spinal needle placement during lumbar puncture. Higher needle velocities resulted in lower peak forces encountered during the puncture of ligament during the epidural procedure. Unfortunately, this work does not report any sample size or statistical evaluation and is difficult to compare with the present study. In our study, there was no statistically significant effect of needle velocity on the slope of the load vs. displacement curve during needle penetration, although the power of this evaluation of needle displacement rate was small. Larger sample sizes may provide significant results. The displacement rates chosen in this study reflect a range, which are realistic in terms of normal surgical practice. The relationship between the resistance forces offered to hollow injection needles and those encountered by solid suture needles, however, is not known but could differ due to geometrical differences between the two tip types.

Our study is limited in that only one needle design, two sheep tissue types and three test displacement rates and tissue tensions were used. Results may differ with other needle displacement rates, designs and tissue types, and requires further investigation.

5. Conclusion

The resistance forces acting on needles during suturing can be characterized. This data provides groundwork in the rapidly developing field of VR and robotic surgery, as well as providing an ergonomic analysis of the factors involved in needle penetration of skin and other soft tissues.

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