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A Simulator for Measuring Forces During Surgical Knots

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Abstract. In this study new metrics were developed for assessing the performance of surgical knots. By adding sensors to a knot tying simulator we were able to measure the forces used while performing this basic and essential skill. Data were collected for both superficial tying and deep tying of square knots using the one hand and two hands techniques. Participants used significantly more force when tying a deep knot compared to a superficial knot (3.79N and 1.6N respectively). Different patterns for upward and downward forces were identified and showed that although most of the time upward forces are used (72% of the time), the downward forces are just as large. These data can be crucial for improving the safeness of knot tying. Combing these metrics with known metrics based on knot tensiometry and motion data may help provide feedback and objective assessment of knot tying skills.

Keywords. Simulators, Knot Tying, Technical Skills, Surgical Education

1. Introduction

Knot tying is an essential skill that all surgical students' need to master. In a recent study by the American College of Surgeons (ACS) and by the Association for Surgical Education (ASE) it was identified as a topic that should be included in simulation-based skills curriculum.[1] Developing metrics to evaluate the knots is an important step in this direction. These metrics can then be used for providing feedback and establishing objective assessment.

Two types of metrics have been the main focus of previous studies: knot tensiometry [2-4] and motion data [5, 6]. Knot tensiometry measures the strength of the knot's final product. Hanna *et. al.* [2] developed a knot quality score (KQS) which takes into account both the knot strength and the threads strength. KQS has shown to give good assessment of knot security and reflects the knot strength and degree of tightening. Motion data measures parameters such number of movements, time taken

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[2] We would like to thank Micro-Measurements for providing the foil strain-gage hybrid sensor.

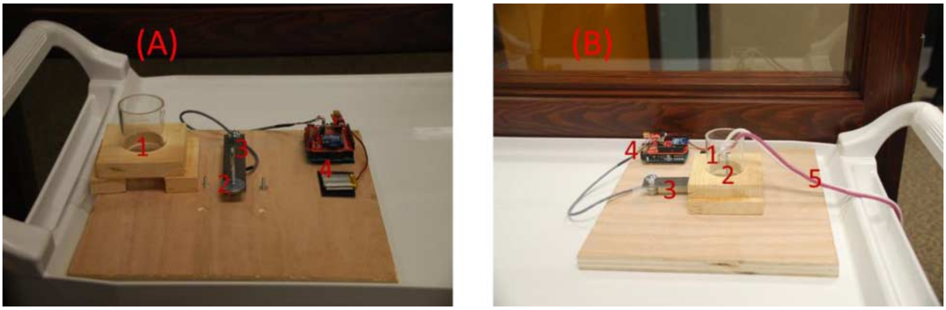

Figure 1. Knot tying simulator. (A) Front view superficial knot configuration. (B) Side view of deep knot configuration. (1) plexiglass tube (2) hook (3) aluminum sheet load cell (4) Arduino + XBEE (5) string

and path length. These data have been able to distinguish between novice and experts and to differentiate the same skill performed in different contexts.[5]

Yet none of these studies measure the forces used and applied on the tissue while tying the knot. It is important to measure and teach proper usage of force during knot tying. For example, in the process of tying a blood vessel by hand, using too much force may tear the blood vessel.

In order to address this issue we designed a simulator that measures the vertical forces used when performing a surgical knot. Surgical residents and medical students were asked to perform a one hand square knot and a two hand square knot in different contexts: a superficial tie and a deep tie. The direction and maximum values of the forces were measured and compared between knot types and contexts. We hypothesize that different force patterns are used for different knot types and contexts and that these forces are measurable by the simulator.

2. Materials and Methods

2.1. Simulator Design

The simulator was similar to current surgical knot tying simulators [7] with the addition of the ability to measure force data. The knots were tied to a screwable hook connected to a foil strain-gage hybrid sensor (Micro-Measurements). The load cell was made from four strain gauges, forming a Wheatstone bridge, glued to a 2.54x12.7x0.16 cm aluminum sheet. The load cell also included an amplifier which was connected to an Arduino Uno for data collection. Data were sampled at 60 Hz and wirelessly transmitted to the computer using an XBEE. In addition a webcam, connected to the computer's USB, was used for collecting video data. Dedicated software was written using Processing [8] to store all the video and sensor data. For simulating a deep tie a removable clear acrylic plexiglass tube was used. The tube had an outer diameter of 5.1 cm, an inner diameter of 4.4 cm and was placed so that the top of the tube would be 3 cm above the top of the hook. The simulator is depicted in Fig. 1.

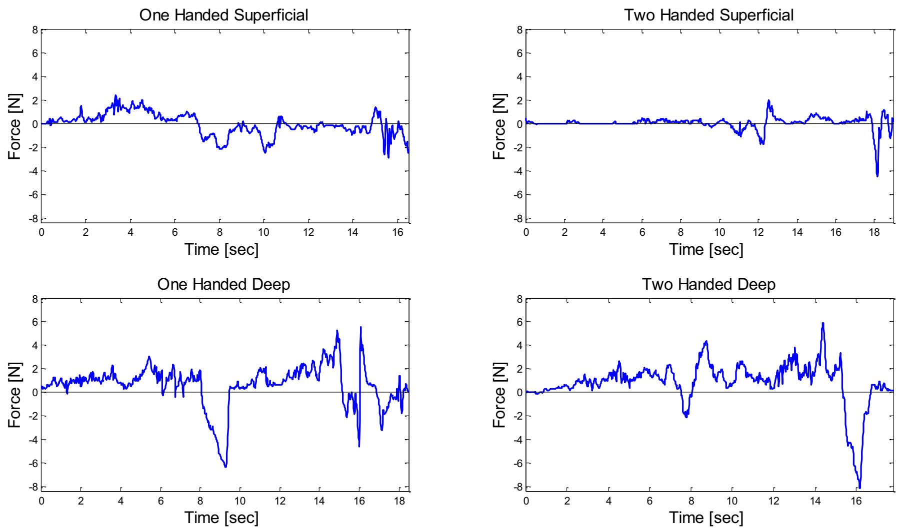

Figure 2. Force data measured for one participant performing all four knots.

2.2. Data Collection and Analysis

Nine participants (7 female, 2 male) gave informed consent to the protocol which was exempt by the University of Madison Institutional Review Board. One participant was a medical student and the rest were surgical residents. All participants had prior clinical experience in knot tying. Using a practice string participants were asked to perform four type knots.

- A superficial one hand square knot
- A superficial two hand square knot
- A deep one hand square knot
- A deep two hand square knot

For each knot three scores were extracted from the sensor data: the maximum upward force, the maximum downward force and the percent of time upward force was used. The last score was calculated by dividing the time the upward force was used by the total time. All data were analyzed using Matlab 2014a (The MathWorks Inc., Natick, MA, 2000). Repeated measures ANOVA statistics were performed using IBM SPSS statistics version 22 (IBM Corp., Armonk, NY).

3. Results

A sample of the forces used by one participant is shown in Fig. 2. The maximum upward forces were significantly higher for deep knots compared to superficial

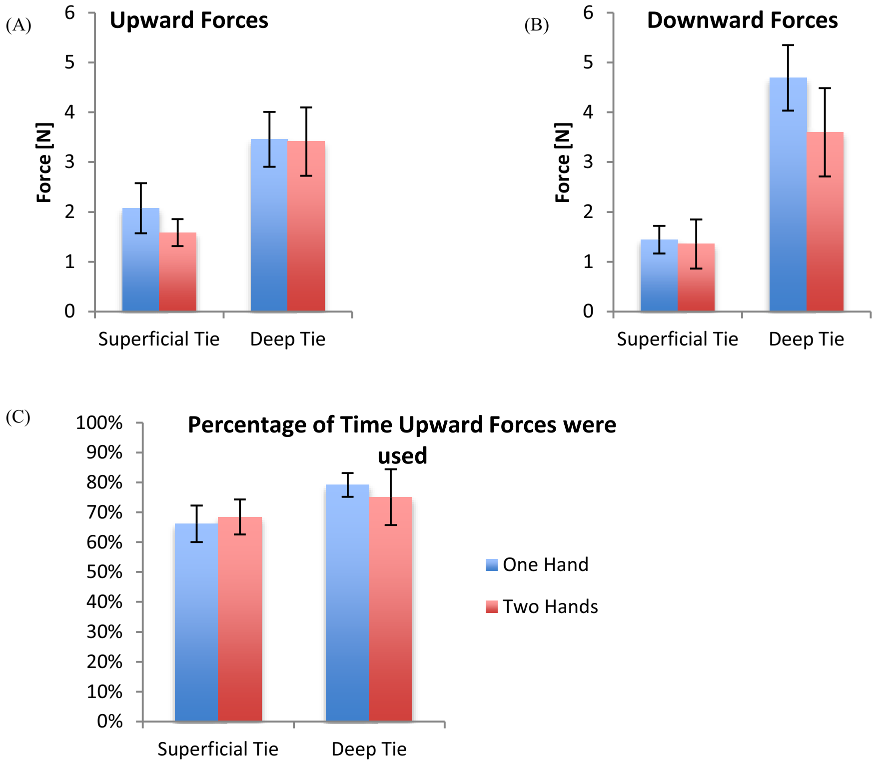

Figure 3. Summary of metrics measured: average of maximum upward forces (A) average of maximum downward forces (B) percentage of time upwards forces were used (C).

(F(1,8)=12.998, p=0.007). Similarly, maximum downward forces were significantly higher for deep knots compared to superficial (F(1,8)=28.02, p=0.007). There was no significant difference between the maximum forces used for the one technique compared to the two hand technique, yet there was a trend showing that higher forces were used for the one hand technique.

There was no significant difference between the max upward forces and max downward forces. However, overall upward forces were used more frequently than downward forces for all knot types (Fig 3C). There was no significant difference between the different knot types in the time upward forces were used.

4. Discussion

A simulator for measuring the forces used during tying surgical knots was developed and evaluated. The simulator was tested for different knot tying techniques and in different contexts. Changing the context from superficial to deep caused significant differences in the maximum forces measured. As anticipated, in the latter higher forces were used. Changing the technique from one hand to two hands only showed a small trend of higher forces used in the one, however this was not significant and more data is needed. It was interesting to see that most of the time upward force was measured, yet the higher peak forces where similar for both downward and upward forces. While further work is needed, this might suggest that although upward force is more common, caution should be used when applying downward forces since short and strong peaks were measured in this direction (Fig. 2).

The load cell used in the study had a good dynamic range for the values measured. Since there was no prior data, initial piloting used a 50N load cell. This was switched to the current load cell which had a dynamic range of 10N which seemed more appropriate. This study used a test string, typically used in simulators for initial practice of tying techniques. Further work should include using a variety of sutures commonly utilized in the operating room. This might also influence the force ranges measured. The hook used in the study was problematic. In some cases it was observed that when downward force was used the knot would slip down the hook to the vertical area. This means that the total downward forces might be slightly higher than presented. Future versions will include a method for preventing the thread from slipping.

With current changes in medical training, it is not feasible and ethical to perform all the training on real patients.[9] Simulators provide a safe and controlled environment for training and assessing.[10, 11] Adding sensors to the simulator provides means for objective measurements and quantification of performance.[12, 13] In this study we measured forces applied during the performance of a hand surgical knot. To the best of our knowledge this is the first time these forces have been measured. We believe this information is valuable for defining the safe range of forces that should be used. Moreover, combining these data with tensiometry and motion data will provide better feedback and a more complete assessment of this fundamental skill.

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