402 - Design Excellence - 23 - knot_too_tight - Executive Summary

Surgical Suture Training: Medical simulations are essential for bridging the gap between training and real-world clinical skill application, including suture techniques in medical and veterinary fields. Proper suture tension is critical for wound closure integrity, promoting healing, and preventing tissue damage or knot failure. However, current training methods rely on subjective instructor evaluation and repeated practice. Existing training tools either lack real-time feedback, are not commercially available, or only measure tension in the first knot throw. As a result, there is a clear need for a practical, standardized training device that objectively evaluates suture knot quality and provides immediate feedback.

Camera-Based Machine Learning For Knot Assessment: The design is an integrated, camera-based system that captures images of surgical knots and processes them through a machine learning network to classify knot tightness as adequate or inadequate. The system outputs real-time feedback, providing a foundation for objective training and assessment.

A 200-image dataset of tight and loose square knots was created and validated by the client. To maximize the impact of a limited dataset, two additional datasets were derived from the original image set using contrast enhancement or binarization, improving edge detection and reducing background noise. Each of the three datasets were compared using K-Fold Cross-Validation to select the one that yielded the highest model performance. Based on the K-Fold results, a novel ResNet50 Convolutional Neural Network (CNN) was trained in PyTorch using the unedited, original dataset. After validation, the model was successfully integrated on a Raspberry Pi and all hardware components were housed in a self-contained module with a custom 3D-printed stand.

Knot Processing Workflow: The system features a fixed-focus camera that captures consistent images for analysis. Users place a suture pad under the camera and press a button to initiate the workflow. A preview is displayed of the camera view until the button is pressed a second time. The camera captures an image to be analyzed by the onboard CNN. Feedback is provided via LEDs: yellow for processing, green for an adequate knot, and red for an inadequate knot. At the system level, latency was measured to confirm that the prototype provides timely feedback suitable for practical training use. Hardware validation included functional testing of the camera, LEDs, and user input button to ensure reliable operation.

Model Performance Evaluation: The model was evaluated using standard metrics such as accuracy, precision, and F1-score, with K-Fold Cross-Validation (n=6) to ensure robustness and repeatability across the dataset. Heatmap visualizations were utilized to confirm that the model correctly analyzed relevant features in the knot, and all images and predictions were logged for ongoing verification.

Simulation Training Impact: The final prototype system successfully generates real-time knot classification feedback with an accuracy of 75%, offering a standardized method for identifying adequate and inadequate suture knots with a processing interval under 4 seconds. By integrating this robust training system into medical and veterinary education programs, suturing proficiency can be improved at earlier stages of training. Faster development of suturing expertise through reliable feedback will lead to better-prepared surgeons, accelerated training, and a reduction in suture failure rates in patients.