Knot Strength – A Mechanics-Based Investigation

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Abstract

Knots play a crucial role in diverse applications, ranging from securing surgical wound closures to facilitating complex biological processes such as DNA tangling. Despite their routine use in fields such as sailing, climbing, and surgery, current knowledge about knot mechanics is largely based on empirical data and practical experience rather than a mechanics-based understanding. In surgery, this gap has led to significant variability in knot-tying techniques among physicians and inconsistencies in defining what constitutes a secure knot (1). Knots are inherently complex mechanical systems due to the interplay of topology, geometry, self-contact interactions, and elasto-plastic material behavior. Existing analytical models based on Kirchhoff's theory for elastic rods are unable to fully capture the functional behavior of physical knots (2). Moreover, until recent years, the computational expense of finite element method (FEM) simulations for rods has further limited advances in knot mechanics. Recent work by Johanns *et al.* (3) identified the key factors influencing the mechanical strength of surgical sliding knots, offering a crucial foundation for developing safer knot-tying techniques. Their experimental and numerical findings showed a consistent power-law relationship between the knot strength and the applied pre-tension across various elastoplastic filaments, with an exponent of 1.6. However, the underlying mechanics driving this non-linear behavior remain unclear.

In this talk, we present the latest advancements in our study of the mechanics of knots, building on the findings of Johanns et al. (3). We have analyzed the strength of multiple knot configurations, exploring a variety of materials and topologies through precision experiments and systematic FEM simulations. Specifically, we have investigated multiple topologies, including a single loop tied around a straight rod, two consecutive loops, and the clove hitch knot. These configurations were examined both when tied around another rod of the same diameter and around a thicker rigid cylinder. Our results evidence three distinct regimes for the behavior of the knot strength as a function of the applied tension: (i) loose knots, when there is no continuous contact between both rods (ii) a nonlinear (power-law) regime, with an exponent 1.6 and (iii) a linear regime observed in (3). This mechanical behavior has been consistently observed across all materials tested, including elastomeric rods (vinyl polysiloxane, VPS), ropes, and Nitinol wires underscoring that the mechanisms governing knot strength extend beyond pure elasticity. In parallel to the experiments, we conduct FEM simulations, which provide additional physical insight; the contact pressure field data reveals the same scaling as the knot strength for the tested knots. To probe further into the underlying mechanics, we extend our study to even simpler contact configurations, such as

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the Capstan problem, toward isolating the physical ingredients underlying knot strength. By bridging the gap between empirical practice and mechanics-based modeling of knots, we anticipate that this research will offer a robust foundation for optimizing and rationalizing knot designs, enhancing safety and efficiency in both traditional and emerging applications, including the development of protocols for tying safer knots in critical fields such as surgery and climbing.