A NOVEL METHODOLOGY TO COMPARE GRASP QUALITY: APPLICATION TO TWO DOMINANT TENDON-DRIVEN DESIGNS

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INTRODUCTION

The design of biologically-inspired tendon-driven systems for grasping and manipulation is a longstanding problem [1]. Some advantages of tendon-driven over torque-driven systems include light weight, small size, high speed, remote actuation, and significant *design flexibility* in setting moment arms and maximal tendon tensions [2]. This allows optimization of system output capabilities for a particular task.

Previous research on grasp quality for tendon-driven hands has computed a grasp quality metric based on a very specific, pre-defined task wrench space [3]. However, they note that their methodology, which utilizes a linear programming approach, does not generalize to the full set of feasible grasp wrenches.

Here we demonstrate a comprehensive technique for computing the full set of feasible grasp wrenches for any arbitrary tendon-driven finger topology and grasp configuration, allowing the calculation of global grasp quality metrics. To the best of our knowledge, this is the first time that the complete exploration of grasp capabilities is possible for arbitrary tendon-driven hand designs. We present this complete analysis for two- and three-finger grasps performed by 3D fingers, each with four kinematic degrees of freedom (DOFs, one ad-abduction and three flexion-extension joints), with two different tendon routing.

METHODS

The tendon routings analyzed are shown in Fig. 1. The link lengths were 2cm and all moment arms were 5mm. Fig. 1a shows a “2N” design which has eight tendons (N is the number of DOFs) and Fig. 1b shows an “N+1” design, which has five tendons. The sum of maximal tendon tensions is 1000N, which is divided up evenly among the tendons for each finger.

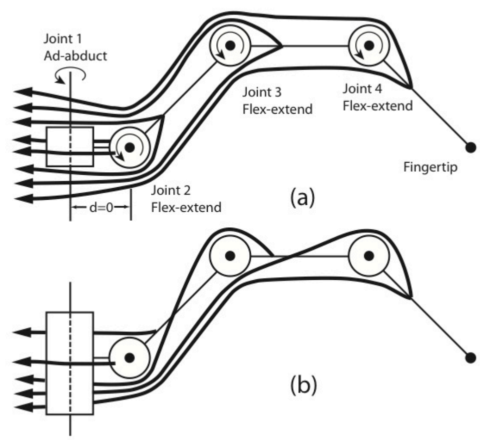

Figure 1: Tendon routing designs analyzed. (a) 2N design. (b) N+1 design.

The fingertip force production capabilities for these two designs are determined by calculating the feasible force set, which is a function of tendon routing [4]. After the feasible force sets are calculated, they are intersected with friction cones to produce a feasible object force set. This set represents the forces that can be applied to the object by each fingertip, and it is illustrated in Fig. 2a.

The feasible object force sets are combined to determine the feasible object wrench set, the set of all forces and torques that can be resisted (i.e., in 6-dimensional wrench space: 3 force dimensions and 3 torque dimensions) [4]. The units of the 6-D wrench space are all in N, as torques are scaled to N by the radius of the object.

Two metrics of grasp quality can then be determined from the feasible object wrench set. The first, which we call the *characteristic length*, is based on the volume of the set, and is calculated using the following formula:

$$Characteristic\ Length = \left(\frac{6V}{\pi^3}\right)^{1/6}$$

This is a linear measure that is equal to the radius of the 6-D ball with the same volume as the 6-D set.

The second metric is the *radius of the largest ball*, centered at the origin, that the 6-D set can contain. This is the "weakest wrench magnitude" that can be resisted by the grasp [5].

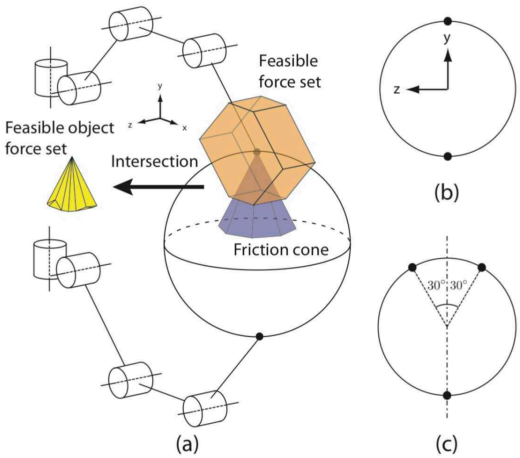

Figure 2: (a) Feasible force set intersected with friction cone. Also, isometric view of 2-finger grasp. (b) Front view of 2-finger grasp. (c) Front view of 3-finger grasp.

RESULTS AND DISCUSSION

The results for each tendon routing and grasp configuration are shown in Fig. 3. For the nominal design, and upon Monte Carlo perturbations of the moment arm lengths, maximal tendon tensions, and link lengths, we see clear trends where the 3-finger grasps outperform 2-finger grasps for these finger placements.

It is not surprising that the 3-finger grasps outperform 2-finger grasps. However, the comparison of 2N vs. N+1 designs, while having the same sum of maximal tendon tensions, was not previously known, nor is it necessarily obvious or intuitive. We see some general advantages to the 2N design, but there exist N+1 designs (which we can identify) that reach high performance with fewer tendons.

This work demonstrates that our method allows calculation of global grasp quality metrics for *any* tendon routing, maximal tendon tension distribution, moment arm values, and link lengths, which has not been accomplished previously, to the best of our knowledge. This now enables us to use optimization techniques in current studies.

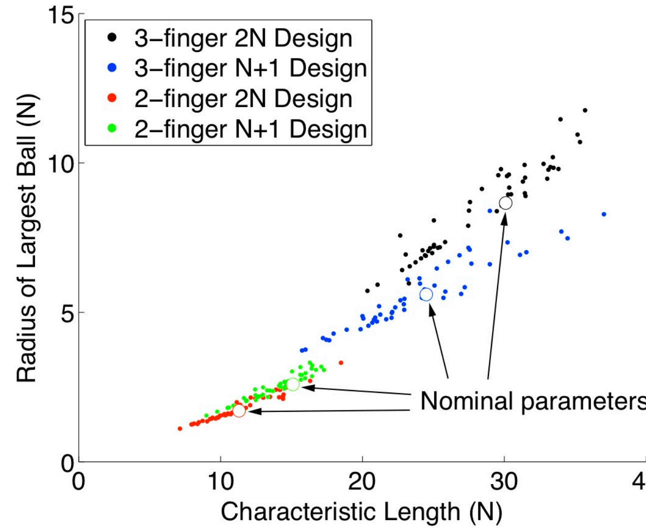

Figure 3: Grasp quality results for nominal (large markers) and 50 Monte Carlo simulations (small markers) for uniformly distributed ±20% perturbations of moment arm, link length, and maximal tendon tension parameters for each design.

In addition, the framework we use in this study can predict the grasp-restoration quality and efficacy of various tendon transfer procedures, which is the subject of current work.

Our method also has very good computational speed and efficiency even if run on a desktop computer. The evaluations took between 1.7 and 39.9 s to complete, depending on hand design and configuration. This enables the use of this methodology with iterative optimization algorithms.

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