Elastic transmission mechanisms: multiport models for human-like compliant grasping in robotic hands

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Abstract— **What is often vexing when considering human grasping and robotic grasping in the same context is that the point of departure is very different; robotic grasp theory traditionally begins at the contact points with the object, and studies of human grasping begins at muscle activation. It would serve well to build an intellectual bridge between the idea of muscle activation in the human hand and the existing mathematical tools of of robotic grasp theory. This paper presents a linear compliance model which can mechanically enforce a prescribed actuator/finger tendon relationship by an elastic transmission mechanism, thereby bridging these areas.**

I. INTRODUCTION

Researchers have known for some time that adding compliance to a robotic hand design allows it to conform to an object of uncertain size and shape [1]. Adding compliance obviates the need for exact certainty in the planning of a grasp. This same principle is involved in human grasping.

Santello's concept of postural synergies [2] represented a very plausible suggestion for how a human cognitively plans a grasp, but does not go so far as to demonstrate how that cognitive ideal is physically implemented in the biomechanical machinery of the human hand. If the robotics community wishes to capitalize on the elegance and robustness of human grasping, it must incorporate some key principles inherent in the musculature of the human hand. The key is to capture these governing principles in a way that can be implemented by mechanical engineering hardware.

This paper suggests that a multi-port linear spring coupling model can capture with reasonable fidelity the most basic motions of human grasping that arise from human musculature and neural coupling. An elastic transmission can then be constructed with the same multidimensional compliance characteristic, and a robotic hand using this engineering part in conjunction with a simplified biologically-inspired tendon structure will display basic grasping motions similar to those of the human hand. This method assumes that nonlinearities in the system are predominantly due to tendon insertions, changing moment arms, and the hand Jacobian. It is plausible that the brain inverts the nonlinear portion and plans the grasp based on a linear compliance model.

II. FINGER INDIVIDUATION AND COUPLING

The position of the various components of the finger, both at rest and in movement depend on a delicate balance of forces generated on the flexor and extensor surfaces. These musculotendinous units act on the metacarpophalangeal (MP), proximal interphalangeal (PIP) and distal interphalangeal (DIP) joints of the finger. Some of these motor units can apply force individually to any one digit to produce an isolated and independent movement. Others act in unison on multiple digits at once. This juxtaposition of coupled and independent motors limits the absolute number of unique positional configurations while allowing a remarkable degree of independent finger motion [3].

The tendons of the flexor digitorum superficialis (FDS) each arise from a separate muscle belly and are therefore able to produce independent digital PIP joint flexion. In contrast, the flexor digitorum profundus (FDP) tendons to the middle, ring and small fingers arise from one common muscle belly and are incapable of giving rise to independent digit flexion. Only the FDP to the index finger has a distinct muscle belly able to move the corresponding digit in isolation [4], [5].

The extrinsic finger extensors are the extensor digitorum communis (EDC), the extensor indicis propius (EIP) and the extensor digiti minimi (EDM). Dorsally in the hand the tendons of the EDC are interlinked by intertendinous connections called juncture tendinae. These connections are especially well developed between the ring and middle finger EDC tendons. The result of this system of intertendinous links is that it is difficult to impossible to produce independent extension of either the middle or ring finger while the other is held flexed. Independent extension of the index and small fingers is facilitated by the EIP and EDM tendons which have their own separate muscle bellies and insert exclusively on their respective targets [4], [6].

The intrinsic control of the fingers consists of the interossei, lumbricals, and hypothenar muscles. Their function is to produce MP flexion and PIP/DIP extension. They also produce adduction/abduction of the fingers. The intrinsic system has no interdigital connections [5].

A complete understanding of hand function as a whole necessarily entails considering the interplay of motor unit combinations and fixed elements connecting them. The available configurational possibilities for a given finger depend very much on the positions of adjacent digits. For a robot hand to function anthropomorphically this system of motion coupling may need to be reproduced.

III. MULTIPORT ACTUATOR-TO-TENDON MAPPINGS

Consider a hand with n finger tendons and m actuators. For an *underactuated* robotic hand design, $m < n$. A linear multiport mechanism such as that shown in 1a describes

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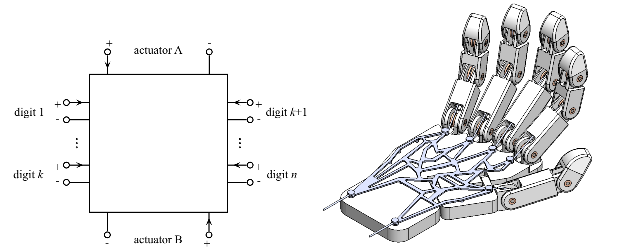

(a) multiport network (b) compliantly coupled hand

Fig. 1. (a) Diagram of a multiport network coupling actuator forces and displacements to finger tendon forces and displacements. Multiport networks are a tool used in circuit theory to accurately and concisely describe the input-output behavior of a network when the network itself is too complicated or is poorly known. (b) Hand with an elastic transmission mechanism that can be modeled by a multiport network. This couples a small number of actuators to coordinated motions of the fingers.

the relationship between (actuator and tendon) forces and (actuator and tendon) displacements as follows:

$$\begin{bmatrix} F_1 \\ \vdots \\ F_{n+m} \end{bmatrix} = S \begin{bmatrix} \delta_1 \\ \vdots \\ \delta_{n+m} \end{bmatrix}. \tag{1}$$

Each F_j is the force corresponding to a given finger tendon or actuator, and each δ_j is the corresponding displacement. S is a (symmetric, positive definite) matrix with units of stiffness, and can be easily identified for a physical elastic transmission mechanism using simple experiments. If S is not diagonal, extensions of a given tendon will produce forces on neighboring finger tendons.

For purposes of grasp planning and control, however, the mapping from actuator to finger tendons, described in Equation (2), is of greater interest. This makes use of the *forward transmission matrix* Λ. Λ has heterogeneous units, but can be partitioned into four submatrices, each having the same units. γ is a null space term that arises because $n \neq m$ (Λ is not square). Physically speaking, γ reflects the ability of a compliant robotic hand to conform to an unknown object.

$$\begin{bmatrix} F_1 \\ \vdots \\ F_n \\ \hline \delta_1 \\ \vdots \\ \delta_n \end{bmatrix} = \Lambda \begin{bmatrix} F_{n+1} \\ \vdots \\ F_{n+m} \\ \hline \delta_{n+1} \\ \vdots \\ \delta_{n+m} \end{bmatrix} + \boldsymbol{\gamma} = \left[\begin{array}{c|c} \Lambda_{11} & \Lambda_{12} \\ \hline \Lambda_{21} & \Lambda_{22} \end{array} \right] \begin{bmatrix} F_{n+1} \\ \vdots \\ F_{n+m} \\ \hline \delta_{n+1} \\ \vdots \\ \delta_{n+m} \end{bmatrix} + \boldsymbol{\gamma}. \tag{2}$$

Equation (2) looks very similar to previous grasping formulations (e.g. [7]); there is a set of basis vectors relating actuators to outputs plus a null space term. What is different about this formulation is that the basis vectors are intimately tied to the physical compliance of the hand. This gives it a direct connection to the physical manifestation of the part.

The $\Lambda_{i,j}$ and γ_j are related directly to the matrix S. Designing a hand with a desired actuator-to-finger-tendon mapping becomes a matter of designing a compliant engineering part with an appropriate S matrix so that each degree of actuation corresponds to a human-like motion.

The dimensions of the matrix Λ also gives insight into how many actuator forces or displacements can be independently specified, by solving the block equations in Equation (2) in "displacement control," or "force control" modes.

IV. A Multiple-Synergy Compliant Hand

Grioli, et. al. [8] constructed a compliant single degree of actuation hand whose motion aligns with Santello's most dominant synergy. The University of Tulsa (TU) Hand, shown in Figure 1b, is a biologically inspired underactuated robot hand. Each of two synergies will be controlled individually by one of two extrinsic actuators, enabling it to achieve a wider variety of useful postures than single-synergy hands. The actuators' force and displacement will be transmitted through an elastic element, or compliant web, to the finger tendons.

The web will be built up of small, interconnected compliant mechanisms to approximate a desired S matrix as closely as possible. The force and displacement characteristics of the entire web will be assigned, first by modeling each constituent element's force and displacement characteristics, and then by considering their connections. The design of the fingers' tendon relationships will incorporate the anatomical features in Section II.

The advantages of the TU Hand's underactuated design are low weight, compactness, and simplicity, making it suitable for a prosthetic device, while the variety of postures composed from its two synergies and physical compliance allows the hand to conform to a variety of objects.

V. Future Directions

Key features of human grasping arise from human hand musculature. The TU hand incorporates a linear compliance model for finger coupling as an implementation of multiple actuated synergies. It will be used to evaluate the fidelity of the linear compliance model with respect to human grasping.

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