Position and Force Constraints in Underactuated Tendon-Driven Systems

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Abstract— **This extended abstract explores how tendon routing can constrain a robot system to operate with fewer actuators by imposing either position or force constraints on the joints. Since these constraints significantly influence the resulting robot motion characteristics, it is essential to understand the relationship between the constraint types and robot motion characteristics. To this end, we classify tendon routing strategies into two types—position-constrained tendon routing (PTR) and force-constrained tendon routing (FTR)—based on the nature of constraints imposed on joint motion. By analyzing the Tendon Jacobian and its null space, we reveal how underactuation facilitates *adaptable motion*–the system's ability to respond flexibly to external contact. To validate this concept, we simulate multi-finger grasping tasks with different constraint configurations. The results show that force-constrained routing enhances adaptability, increases contact points, and improves grasp stability compared to position-constrained routing. These findings provide design insights for tendon-driven robotic systems.**

I. Introduction

Determining the appropriate number of actuators for a tendon-driven robotic system, given its degrees of freedom (DOF), remains an interesting challenge in robot design. Although a fully actuated system may offer well-defined controllability, it may introduce substantial trade-offs in terms of cost, weight, complexity, and reliability especially when the system has a high number of DOFs. In contrast, utilizing fewer actuators—while preserving functionality through mechanical coupling—can mitigate these drawbacks, though it may limit controllability. Interestingly, these limitations can also be beneficial: the robot system may perform adaptive motions in response to external environments and demonstrate robustness to external impacts, owing to its redundant DOFs. From this point of view, since full-DOF control is not always necessary, carefully deciding the number of actuators and corresponding tendon routing can be an effective strategy for designing compact, simple, robust, and environmentally adaptive robotic systems.

One possible design strategy for fewer actuator use is interpreting the concept of *constraints* imposed by the tendon routing, as illustrated in Fig. 1 [4]. For example, a single

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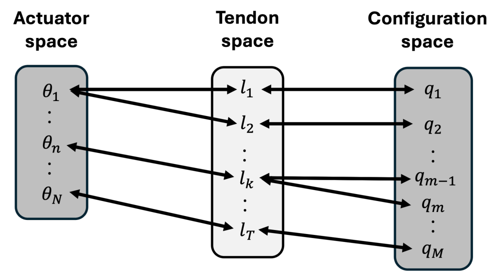

Fig. 1. Kinematic relationships between three vector spaces in tendon-driven robots.

actuator (θ_1) can drive two tendons (l_1, l_2) that actuate two joints (q_1, q_2), creating a position-constrained system in which the actuator position fully determines the joint configuration–e.g., we can explicitly know the tendon excursion length (l_1 and l_2) that can be used to calculate the two joint angles (q_1 and q_2).

Conversely, when a single tendon is routed across multiple joints, the actuator displacement (θ_n) or tendon length (l_k) influence all connected joints simultaneously. In such cases, individual joint angles cannot be uniquely determined from the actuator state alone. However, due to uniform tension along the tendon path, the force applied to each joint is consistent, resulting in a force-constrained configuration. Based on this different possibility of routing the tendon, we can classify tendon configurations into two categories: *position-constrained tendon routing* (PTR)[1] and *force-constrained tendon routing* (FTR)[2].

Understanding how each routing strategy shapes the resulting motion patterns is essential when designing the robot system with fewer actuators. Such understanding enables us building the system with minimized cost and mechanical complexity without compromising controllability, thereby achieving efficient and robust underactuated robot designs.

In this extended abstract, to provide a systematic understanding of tendon-driven underactuated robotic systems, we classify and analyze how these constraint types affect grasping behaviors, supported by mathematical modeling and simulation-based validation.

[1]This routing, known as *postural synergy* [5, 6] or *branch tendon* [7], is inspired by patterns of human movement [8]. These constraints are implemented by pulling multiple tendons with a set of spools connected in parallel [5, 6] or tying them into a single tendon [7].

[2]This routing is known by various names, including under-actuated tendon routing [9, 10], tendon transmission with series transmission matrix [11], differential mechanism [12, 13], and adaptive synergy [5]. While 'underactuated tendon routing' is widely used, distinguishing PTR and FTR allows a clearer understanding of the distinct motion constraints they impose.

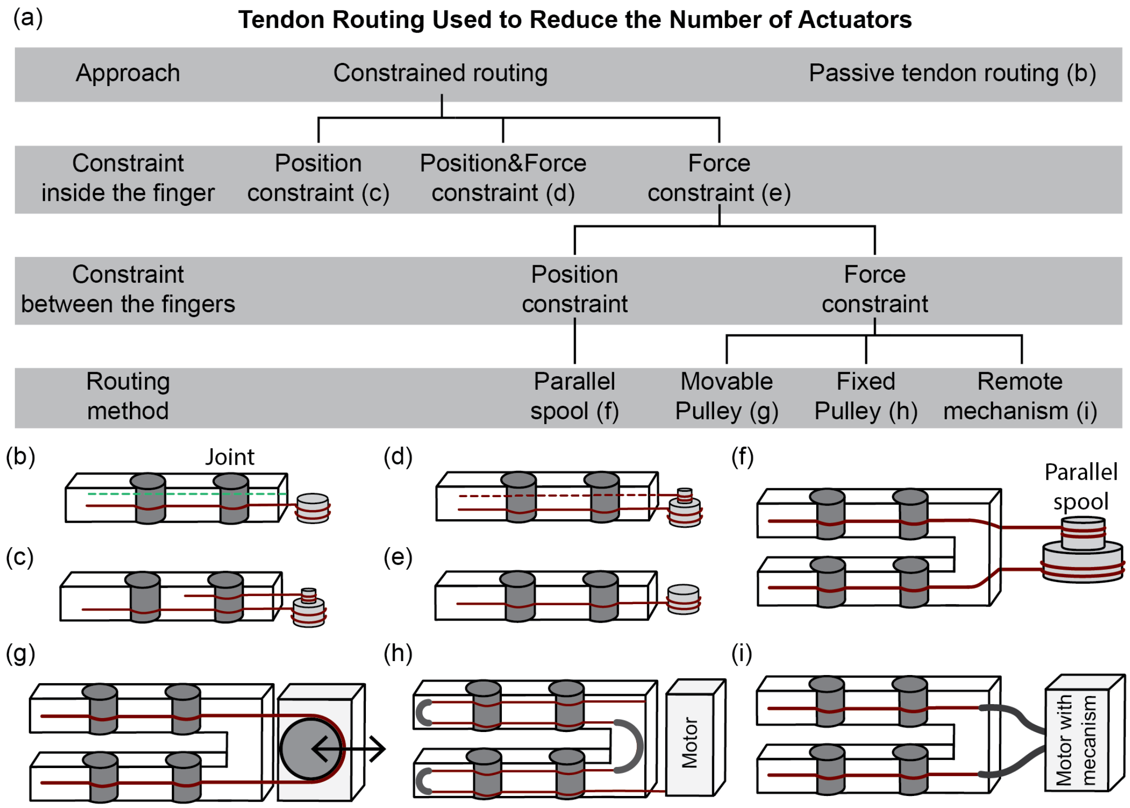

Fig. 2. Tendon routing classifications that enable to reduce the number of actuators. (a) Overview of classification. (b)–(e) show schematics of representative routings for a single linkage; (f)-(i) show the routings for multi-finger application. Detailed explanations of each tendon routing scheme are provided in section II.

II. Classification of Tendon Routings That Enable Fewer Actuators

Various tendon routing strategies have been developed to reduce the number of actuators based on different functional requirements (Fig.2). A basic approach for routing a tendon to a single linkage involves routing it to span multiple joints within the linkage (Fig.2e). Since the tension remains the same in the tendon, this routing constrains the force/torque applied to the joints.

However, since tendons can only transmit tensile force, an additional passive tendon is often routed in the opposite direction to use fewer actuators when motion in a specific direction is less critical (Fig. 2b) [14]. In some cases where passive torque is not desirable [9], a common alternative is to use two active tendons–each dedicated to one direction of motion–enabling bidirectional actuation(Fig. 2d)[15, 16]. In this case, since the motor actuates two tendons simultaneously, it necessarily applies position constraints between two directional motion. Therefore, finding appropriate initial length of two tendons is important to make reliable actuation [17].

Position constraints can also be applied within a linkage (Fig.2c). It can be established by attaching multiple tendons at the motor that pass the linkage; an alternative approach involves tying the tendons together at a location other than the motor, depending on design preferences. This configuration, where tendons are joined at a point away from the actuator, is commonly referred to as a branching tendon[18].

When building multi-fingered robotic systems, a practical and scalable approach (Fig. 2f) involves using a single motor to pull multiple tendons, each connected to an individual linkage [19–22]. This configuration imposes position constraints between linkages while applying force constraints to the joints within each linkage. One of the key advantages of this routing method is its scalability—by simply attaching additional tendons to parallel spools, a large number of fingers can be actuated with just one or a few actuators. In some cases, researchers have even developed their robot to make the bi-directional motion of multiple fingers using only a single motor [6]. However, the imposed position constraints necessitate careful calibration of the initial tendon lengths to ensure consistent and effective motion.

Since position constraints can limit motion adaptability—an issue further examined in this paper—some researchers have proposed routing tendons without imposing such constraints (Fig. 2g–i). These methods typically involve a single tendon routed by a motor through joints across multiple linkages, enabling more flexible and adaptive motion. In this approach, to route the tendons to pass one linkage to other linkage, several approaches are possible depending on different requirements. A common way is using movable pulleys between the linkages [23]. In soft robots, however, alternative methods have been preferred as it required certain amount of space for movable pulleys' traveling length [24]. Researchers have explored using fixed pulleys instead of movable pulleys to make their robots compact [5, 9, 17]. In this routing, the tendon is not fixed to the end of the link but rather passes through a fixed pulley at the link's end and then loops back to the base of the link (Fig. 2h). However, this routing introduces friction-related problems (e.g., hysteresis, uneven force distribution, reduced efficiency, and reliability) due to the overlapping friction along the tendon path [25]. The impact of this friction is not negligible because the friction accumulates along the tendon. This routing has been referred to as *augmented adaptive synergy* [5, 26] or *soft tendon routing* [9] in previous works.

Recently, to solve these size and friction issues, methods of locating movable pulley [25] or differential mechanism [27] at the remote-actuator were proposed (Fig. 2i). Since these mechanisms use low-friction mechanical components, the friction can be dramatically reduced. Further, the robot remains compact even using these components because they are included in the actuator, not the robot body. However, the overall tendon should be sufficiently long to locate the actuator far from the robot itself, tendon stiffness was reduced. The decrease in tendon stiffness induced the actuation tendons to be easily elongated which forced to use of bigger actuators by requiring more stroke; it also reduced the control performance by decreasing the actuation bandwidth.

Recently, a method of combining the routing that uses fixed pulley (Fig. 2h) and that uses remote mechanisms (Fig. 2i) has been proposed to overcome possible issues. This approach, known as Dual-Tendon Routing, effectively resolves the practical issues [1].

III. Analysis of Tendon Routings That Enable Fewer Actuators

The analysis on underactuated tendon-driven system can be started from defining *Tendon Jacobian* [11, 28] that defines the relationship between the joint configuration and the tendon configuration as

$$\dot{\mathbf{l}} = \mathbf{J_j}\dot{\mathbf{q}} + \mathbf{R}\dot{\theta} \tag{1}$$

where, $\mathbf{l} \in \mathbb{R}^{n\times 1}$, $\mathbf{J_j} \in \mathbb{R}^{n\times N}$, $\mathbf{q} \in \mathbb{R}^{N\times 1}$, $\mathbf{R} \in \mathbb{R}^{n\times m}$, and $\theta \in \mathbb{R}^{m\times 1}$ are the tendon length, tendon jacobian, joint angle, radius of the motor spool, and motor displacement, respectively. n, N, and m are the number of tendons, the number of joints, and the number of motors, respectively. We assume $m < N$, as this work focuses on reducing the number of motors.

Given that the number of actuators is fewer than the number of joints, the tendon Jacobian in Eq(1) has a null space. Consequently, the infinitesimal change in joint angle ($d\mathbf{q}$) is defined as

$$d\mathbf{q} = \mathbf{J_j}^{\dagger}\mathbf{R}d\theta + \alpha N(\mathbf{J_j}) \tag{2}$$

where $N(\mathbf{A})$ represents the null space of matrix $\mathbf{A}$ and $\mathbf{A}^{\dagger}$ represents pseudo-inverse of the matrix $\mathbf{A}$. α is any arbitrary real number that represents *span* of the null-space. The value of α is determined by the contact torque applied by the external environment [28].

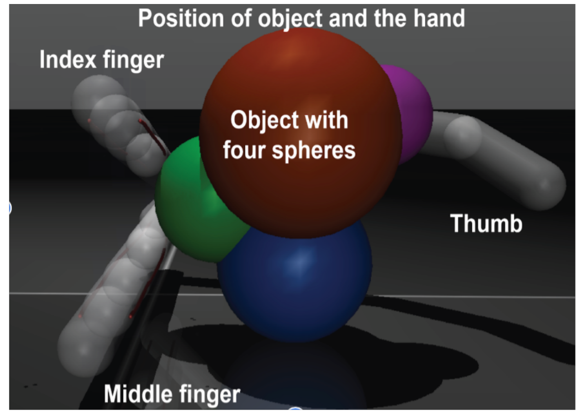

Fig. 3. Simulated object and robotic hand used to evaluate adaptable motion, with the object placed at a predefined position.

IV. Effect of Constraint Types in Grasping Objects

The existence of null space makes it difficult to uniquely determine joint angles from actuator inputs–we cannot estimate joint angle even though we measure the actuator position. This is because α in Eq(2) is determined by force equilibrium rather than kinematics. While this may pose challenges in certain scenarios, researchers have found innovative ways to exploit this property. The null space enables a distinctive behavior known as *adaptable motion*, which emerges when the robot interacts with the external environment. For example, certain joints can continue to move even if others are physically constrained, due to the degrees of freedom preserved in the Jacobian's null space. This adaptability proves especially advantageous in robotic grasping, where it increases the number of potential contact points and promotes stable grasps through force closure.

We previously validated how force and position constraints influence motion adaptability through MuJoCo, one of commonly used simulator for tendon-driven robot simulation, in our earlier work [3]. This work focused on comparing two representative tendon routing strategies commonly used in systems designed to reduce the number of actuators. The first applies force constraints within each finger and position constraints across fingers, effectively coupling the displacement of multiple fingers (Fig.2f). The second applies only force constraints to the joints, without inter-finger coupling (Fig.2g–i). This work briefly summarizes those results to highlight the motion behaviors of underactuated tendon-driven robots.

In this simulation, we used only combination of basic geometric shapes such as cylinders and spheres for simulation, as MuJoCo's contact model tends to be more stable and reliable with primitive geometries compared to complex mesh-based objects. To evaluate the adaptability of the robot's grasp to complex object geometries, we constructed test objects by combining basic geometric primitives such as spheres and cylinders. This approach allowed us to generate a variety of nontrivial shapes while maintaining simulation stability in MuJoCo. An example of the composed object is illustrated in Fig. 3. The object consists of four spheres positioned at predefined locations (all dimensions in millimeters): (1) a blue sphere with a radius of 50 centered at (120, 100, 50); (2) a green sphere with a radius of 40 centered at (120, 50, 90); (3) a magenta sphere with a radius of 30 centered at (150, 100, 140); and (4) a red sphere with a radius of 60 centered at (170, 150, 130). In this experiment, we measured two performance metrics: 1) the number of contact points and 2) the scalar summation of contact force. This is because large number of contact points and scalar summation of contact force highly improves the grasp stability [29, 30].

Simulation results (Fig. 4) indicate that the position-constrained configuration limits the system's adaptability, yielding fewer contact points and lower total contact force. Specifically, the position-constrained setup results in four contact points with a total contact force of 163.01(N), whereas the configuration without position constraints achieves eight contact points and a total contact force of 517.22(N).

V. Discussion and Conclusion

This work demonstrates how tendon routing enables robot actuation with fewer actuators by imposing constraints on joints. We focused on comparing two widely used tendon routing strategies in underactuated robots: (1) a routing method of applying force constraints within each finger and position constraints across fingers (Fig.2f) and (2) a routing method that applies only force constraints (Fig.2g-i). Simulation results demonstrate that removing the position constraint between fingers leads to a more stable grasp by increasing the number of contact points and higher total contact force.

Although this study highlights the advantages of removing position constraints to improve adaptability, the alternative routing method—one that includes position constraints between fingers—offers several key benefits. First, it enables a simpler mechanical design even with a large number of linkages/fingers, as more tendons can be directly employed. Second, it supports sequential or staged motion control by adjusting the initial tendon lengths [14]. Third, this configuration can facilitate coordinated movement patterns across multiple fingers, which may be desirable in specific manipulation tasks.

From this perspective, selecting the appropriate tendon routing strategy should be guided by task-specific requirements, balancing the trade-offs between structural simplicity, controllability, and adaptability. We hope this classification and comparative analysis provides useful design insights for future underactuated robotic systems.

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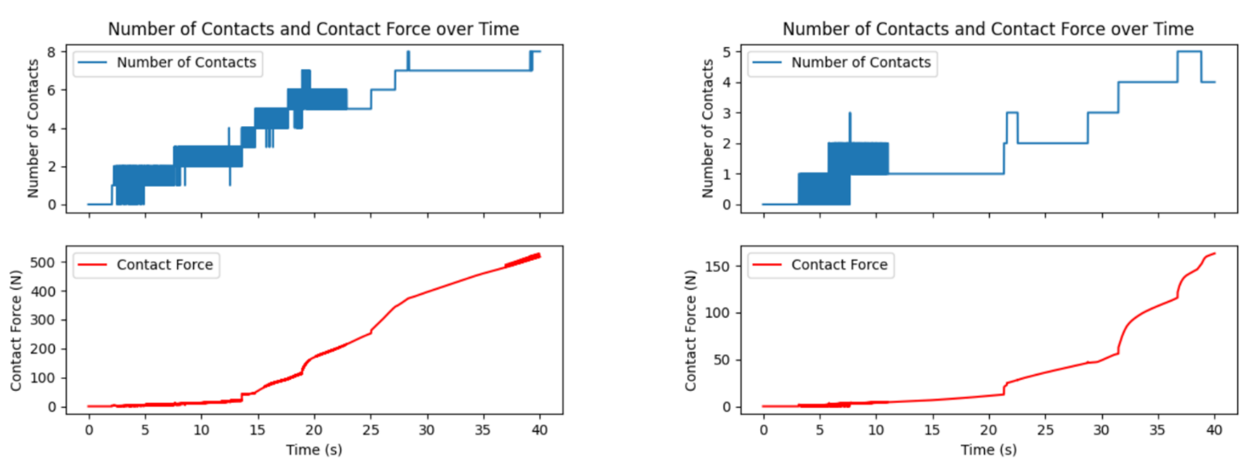

Fig. 4. Number of contact points and total contact force under different conditions: (a) shows results for the configuration with force constraints between fingers, while (b) shows results for the configuration with position constraints between fingers.

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