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Force and Torque studies in Multifinger Robotic Gripper-A Review

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Abstract

This study focuses on the design and development of a tendon-driven multi-finger robotic gripper incorporating compliant springs. The primary objectives include analyzing the forces within the tendons and structural links of the gripper, as well as evaluating the torques at each finger joint. A comprehensive grasp analysis is conducted by simulating the robotic hand interacting with various objects to identify the fingertip contact points on the object surfaces. The hand's performance is assessed by simulating its ability to grasp objects of varying dimensions. MATLAB's SimScape environment is utilized for 3D visualization and simulation of the robotic hand, where finger movements are controlled to perform grasping tasks. The study further investigates the grasp forces to calculate the contact forces and the tendon tensions generated by both the thumb and fingers to ensure a secure grip on cylindrical objects of different sizes, weights, and materials. The mathematical analysis confirms that the tendon tension and internal link forces scale proportionally with the object's weight.

Keywords: *Dexterous manipulation, Anthropomorphic design, Kinematic modeling, Force analysis, Torque and force closure.*

1. Introduction

The domain of dexterous multi-fingered robotic hands remains a prominent and evolving field of research. Two significant challenges in this area are: the development of more dexterous hand architectures, and the enhancement of grasp capabilities, including grasp stability and quality. These areas pose both technological and theoretical difficulties. Over the years, numerous robotic hands with multiple fingers have been engineered; however, there is still a limited body of work addressing grasp planning for fingers functioning collaboratively—essentially acting as multiple coordinated manipulators [1]. A review of previous literature reveals that researchers have proposed a variety of design models for multi-fingered hands, typically incorporating several degrees of freedom per finger to emulate the complexity of the human hand. Over the past twenty years, key concepts such as form-closure and force-closure have been thoroughly explored in the context of robotic grasping. A grasp is considered to achieve form-closure when the object's motion in any direction is impeded by contact points, making it a purely geometric property dependent on object shape and contact locations. In contrast, a force-closure grasp enables the application of arbitrary forces and torques on an object via the contact points, ensuring resistance against any possible motion without external work being applied [2]. Some researchers have established the duality between form-closure and force-closure and proposed conditions for synthesizing planar grasps that satisfy force-closure criteria. A grasp achieves force-closure when the contact forces generated can resist any external disturbances, ensuring the object cannot move or escape from the grip without expending energy. Various computational methods have been introduced to assess and achieve such closure conditions. For instance, one approach developed a method based on the grasp wrench space central axis to determine the necessary and sufficient conditions for equilibrium and force-closure. Algorithms were also proposed for identifying force-closure grasps using multiple hard-finger contacts under a Coulomb friction model. Kralge

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introduced a method to compute independent contact regions on objects using an initial guess of contact points. This method supports diverse contact models, including frictionless point contacts, point contacts with friction, and soft finger contacts. Suhaib presented an optimization-based framework aimed at identifying the most stable grasp for a selected set of contact points. Their approach optimized friction angle parameters to ensure the conditions for stable and secure grasping were met [3]. The current study focuses on designing a kinematically accurate, multi-fingered robotic hand capable of compliant object manipulation. The work is divided into two major components. First, a kinematic simulation of the hand and individual fingers is conducted to evaluate dexterity and available workspace. Second, a grasp analysis is performed to investigate the hand's ability to achieve force-closure grasps. The robotic hand model designed in this study features five fingers with a total of 25 degrees of freedom (DoFs), including 2-DoFs at the carpometacarpal (CMC) joints of the ring, little, and thumb fingers—facilitating movement in the palm arch. The wrist is fixed in the simulation, and its real-life 2-DoF articulation is not considered for simplicity and consistency in analysis. A thorough evaluation of force-closure grasp capabilities and grasp quality is presented. The reachable workspace of the hand defines the maximum spatial boundary for manipulation. The study assumes positive grips, formulated as non-negative linear combinations of basic wrenches. The analysis is limited to wrench systems induced by finger contacts under Coulomb friction conditions. To validate the proposed model and computational algorithm, example cases are explored with different sets of contact points on a variety of object geometries [4].

2. Mathematical Modeling of Force & Torque Analysis on a Multifinger Robotic Gripper

Robotic hands with multiple fingers are typically designed to replicate the structure and function of the human hand, aiming for anthropomorphic resemblance. This resemblance includes both the shape and movement patterns, with the hand size being a critical factor in both design and application—whether integrated into an industrial robotic arm or used in prosthetic systems [5]. Each finger and corresponding structure in a human hand functions independently, and this principle guides the design of robotic fingers. Inspired by the anatomical segmentation of human fingers, this study adopts independently actuated segments to construct the full finger model. The segment lengths for the thumb and fingers are proportionally derived from overall hand length and breadth, with the wrist assumed to be a fixed reference point (origin) for all kinematic calculations [6] [7]. **In the proposed design:**

- The thumb is assigned 5 degrees of freedom (DoFs).
- The index and middle fingers are each modeled with 4 DoFs. [6] [31]
- The ring finger is designed with 6 DoFs, including 2 DoFs at the carpometacarpal (CMC) joint to represent the motion of the palm arch.

The model accounts for:

- Trapeziometacarpal (TM) joint, all five metacarpophalangeal (MCP) joints, and two CMC joints with 2 rotational axes each (for abduction–adduction and flexion–extension). [6] [31]
- The distal interphalangeal (DIP) joints in the fingers each possess 1 DoF, primarily for flexion–extension motion.

Comprehensive kinematic simulations have been conducted to validate the proposed model. These simulations consider joint range limits derived from anatomical data and prior studies [5], ensuring the robotic hand operates within realistic bounds. The kinematic structure is modeled using ideal revolute joints and rigid segments to determine the fingertip locations and overall workspace of the hand. [8] The Denavit–Hartenberg (DH) method is used for frame transformation, allowing the relationship between joint coordinates to be established systematically. Each finger has an individually defined DH parameter set, and transformation matrices are developed accordingly.

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The wrist, acting as the global coordinate frame, serves as the base for all positional calculations. [9] **Anthropometric Parameters and Joint Range Constraints:** To achieve a close resemblance to human hand functionality, the mechanical design includes joints in the palm (metacarpal region) and fingers, similar to biological counterparts. The link lengths between joints are proportionally scaled to human bone lengths, using anthropometric ratios based on hand length (HL) and hand breadth (HB) [10]. Each finger is treated as an open kinematic chain, where each segment is modeled as a link in a robotic manipulator. Accurate modeling of segment lengths is critical for calculating the fingertip position and overall reachability of the hand. Because hand sizes vary between individuals, a general proportional framework is adopted to calculate segment lengths for any specific hand based on measured HL and HB values. For this study, anthropometric data typical of an adult male hand [9, 10] is used. Additionally, joint motion limits and degrees of freedom are designed to reflect those observed in real human fingers, enabling the robotic hand to perform dexterous manipulation tasks effectively. [11]. The anthropometric measurements used for the palm (metacarpal section) and fingers (phalangeal section) are summarized in Table 1 and Table 2, respectively.

Table 1 (Segment T Length for Metacarpal Bones) [6] [31]

Finger	Metacarpal bones	Link
Thumb	$0.251HL$	L_{2T}
Index	$\sqrt{(0.374HL)^2 + (0.126HB)^2}$	L_{2I}
Middle	$0.373HL$	L_{2M}
Ring	$\sqrt{(0.336HL)^2 + (0.077HB)^2}$	L_{2R}

Table 2 (Length for Phalangeal) [6] [31]

Finger	Proximal	Link	Middle	Link	Distal	Link
Thumb	$0.196HL$	L_{3T}	-	-	$0.158HL$	L_{4T}
Index	$0.265HL$	L_{3I}	$0.143HL$	L_{4I}	$0.097HL$	L_{5I}
Middle	$0.277HL$	L_{3M}	$0.170HL$	L_{4M}	$0.108HL$	L_{5M}
Ring	$0.259HL$	L_{3R}	$0.165HL$	L_{4R}	$0.107HL$	L_{5R}

2.1. Locating the Finger Tip

A kinematic framework has been established to determine the position of the fingertip. Using specified joint angles as input, the model computes the fingertip's location relative to the palm's coordinate frame. The Denavit–Hartenberg (DH) parameters for each finger are defined accordingly. The standard form of the transformation matrix is expressed as follows: [31]

$$
{}^{i\text{-}1}T_i = \begin{bmatrix} cosq_i & -sinq_i cos\alpha_i & sinq_i sin\alpha_i & L_i cosq_i \\ sinq_i & cosq_i cos\alpha_i & -cosq_i sin\alpha_i & L_i sinq_i \\ 0 & sin\alpha_i & cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

2.2. Grasp Analysis

A wrench represents the combined effect of a force applied along a line and the resulting torque. It serves as a comprehensive way to describe any force system acting on a rigid body. In essence, both the linear force and the rotational moment are encapsulated within the concept of a wrench as follows:

$$
\boldsymbol{w} = \begin{pmatrix} \boldsymbol{F} \\ \boldsymbol{F * d} \end{pmatrix}
$$

The force equilibrium is:

$$
\sum_{i=1}^{n} \boldsymbol{F_i} = \sum_{i=1}^{n} \boldsymbol{F_i cos\theta_i + F_i sin\theta_i = 0}
$$

$\boldsymbol{F_i cos\theta_i, F_i sin\theta_i}$: The magnitudes of the finger force $\boldsymbol{F_i}$ $\boldsymbol{d_i}$ **:** The position vector of $\boldsymbol{i^{th}}$ finger

The moment equilibrium:

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$$\sum_{i=1}^{n} d_i \times F_i = \sum_{i=1}^{n} d_{iy} \times (F_i cos\theta_i) + d_{ix} \times (F_i sin\theta_i) = 0$$

d_{ix} = perpendicular distance of y component force
d_{iy} = perpendicular distance of x component force

2.3. Contact Models

Various contact models are used to represent the interaction between robotic fingers and grasped objects. Two key factors influence the choice of model: the nature of friction at the contact interface and whether the finger surface is rigid or compliant. Based on these considerations, the commonly used contact models include:

- Frictionless Point Contact (FPC),
- Point Contact with Friction (PCWF), and
- Soft Finger Contact (SFC).

In the frictionless point contact model, there is no friction at the contact interface, meaning the force exerted by the finger acts only in the direction perpendicular to the object's surface. [12]. The point contact with friction model introduces friction between the finger and the object. Using the Coulomb friction model, one can determine the tangential force limits at the contact point, which are dependent on the magnitude of the normal force. In this case, the contact force must reside within a friction cone centered around the surface normal. [13]. The soft finger contact model is an extension of PCWF, where, in addition to tangential and normal forces, a small moment or torque around the normal direction can also be applied at the contact point. In this study, the point contact with friction model is used, with the coefficient of friction (μ) assumed to be between 0.2 and 0.4—typical for interactions involving materials like plastic or metal. The forces applied by the fingers at the contact points are required to remain within the defined friction cone. [14]

2.4. Condition for Force & Torque closure Grasp

In this study, it is assumed that friction exists between the object and the fingers, enabling a secure grip and preventing slippage. The effectiveness of the grasp and the resistance to external forces depend on the orientation and positioning of the fingers on the object. Based on this configuration, the necessary finger forces are determined. To achieve a stable grasp, two primary conditions must be fulfilled. First, the system must satisfy force equilibrium, meaning the sum of all forces acting in both the x and y directions must be zero:

$$\Sigma F_x = 0 \ \& \ \Sigma F_y = 0.$$

Second, the system must also meet moment (torque) equilibrium, where the net moments about the reference point in both x and y axes are zero:

$$\Sigma M_{ox} = 0 \ \& \ \Sigma M_{oy} = 0.$$

A grasp that fulfills both these conditions is considered a force-closure grasp, and the object is said to be in a state of force closure. Additionally, it is required that not all applied contact forces simultaneously reduce to zero—ensuring that the object remains stably held under the influence of non-zero forces. [15] [6]

2.5. Force Closure Condition For Object

To evaluate the force-closure capability of the developed robotic hand, a theoretical analysis is performed using objects of different shapes, dimensions, and weights. The object sizes and weights are selected such that they fall within the operational workspace and payload capacity of the robotic hand. For simplicity, the objects are assumed to have standard geometric shapes. Several sets of contact angles are considered, all falling within the permissible angular range of each finger. In this study, two sample objects are presented to illustrate the method and results clearly. The contact angles chosen for these cases are:

$$\theta_1 = 20^0;\ \theta_2 = 25^0;\ \theta_3 = 30^0;\ \theta_4 = 0^0$$

The other pertinent data are: value of coefficient of Coulomb's friction, **μ** = 0.25 (plastic and metal), weight of the body = 100gm (0.98N), $F_t \leq \mu N$,

where, F_t = Tangential force and **N** = Normal force. In present case F_t = **0.98N.**

2.6. Holding a pyramid object by a multi finger robotic gripper

Referring to Figure below the maximum normal force (N) required, can be calculated as follows:

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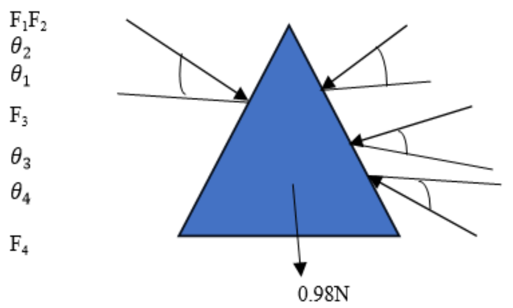
0.98 ≤ 0.25N or 0.98/0.25 ≤ N or N ≥ 3.92N. Dividing this normal force in two equal parts and applying them on the two faces of the object. i.e.,3.92/2 = 1.96N force on the LHS face and 200N force on the RHS face. With F_t = 0.98N, the maximum normal force (N) required, can be calculated as follows: 0.98 ≤ 0.25N or 0.98/0.25 ≤ N or N ≥ 3.92N [6].



F1=Force applied by the thumb
F2, F3, F4 = Forces applied by Index, Middle, Ring finger **for Force Equilibrium:**
The force F1 can be calculated as: **F_1 cos20=1.96,** hence, F_1 =2.087N. By hit and trial method we can calculate the values of all the forces. Hence, F2=0.3922N; F3=0.5295N; F4=0.5687N.

For Torque Equilibrium:
In the pyramid configuration, the first finger positioned on the left-hand side (LHS) face is located roughly at the center of that surface. Fingers two and five are placed arbitrarily near the corners of the right-hand side (RHS) face. The third and fourth fingers serve as manipulative fingers, oriented perpendicular to the RHS face, and are primarily responsible for counteracting the torque generated during the grasp.

In this setup:
The total clockwise torque is calculated to be **0.0784 Nm**
The total counter-clockwise (anticlockwise) torque amounts to **0.0512 Nm**

3. Force and Torque Analysis for Cylindrical Object

3.1. Force analysis

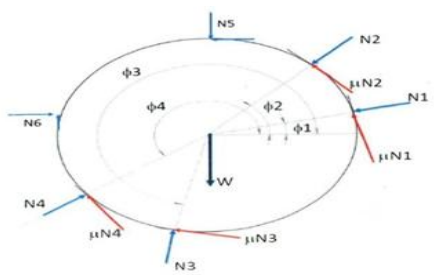
In order to grasp an object using a robotic hand, a certain amount of friction must exist at each contact point between the fingers and the object, as described by the law of static friction. [6] [31].

$$F = \mu N$$

The frictional force is directly influenced by the magnitude of the normal force. The greatest force that a finger can apply to an object acts in the direction perpendicular to the contact surface. For a stable grasp, the system must fulfill the conditions of static equilibrium. This means that all forces—those due to friction at the contact points between the gripper and the object, the object's weight, and the contact forces between the fingers and thumb—must be balanced. By applying the relevant equilibrium equations, it is possible to calculate the forces acting on the finger and thumb segments (phalanges), as well as the tension present in the tendons. [6] [19] [20] [31]. Link 1 is distal link of the finger, link 2 is medial link of the finger, link 3 is distal link thumb and link 4 is medial link of the thumb
N_i = normal force at fink,
μ= coefficient of friction
ϕ_i = in angle between line of action of normal force and horizontal plane
W= weight of the object

Assumptions

- Friction between the tendon and the links it passes through is considered negligible. All joints are assumed to be frictionless.
- The mass of the fingers and thumb is assumed to be insignificant in comparison to the mass of the object being grasped. [21] [22] [31]



Taking $\Sigma_i^n F_i = 0$ for vertical and horizontal direction. For horizontal direction [6] [23] [24].

$$N_1(\cos\phi_1+\mu\sin\phi_1) + N_2(\cos\phi_2+\mu\sin\phi_2) +$$

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$N_3(\cos\phi_3+\mu\sin\mu_3) + N_4(\cos\phi_4+\mu\sin\phi_4) + N_5(\cos\phi_5+\mu\sin\phi_5) + N_6(\cos\phi_6+\mu\sin\phi_6) = 0$

For vertical direction

N1(sinϕ1+μcosϕ1) + N2(sinϕ2+μcosϕ2) + N3(sinϕ3+μcosϕ3) + N4(cosϕ4+μcosϕ4) + N5(sinϕ5+μcosϕ5) + N6(sinϕ6+μcosϕ6) + W=0

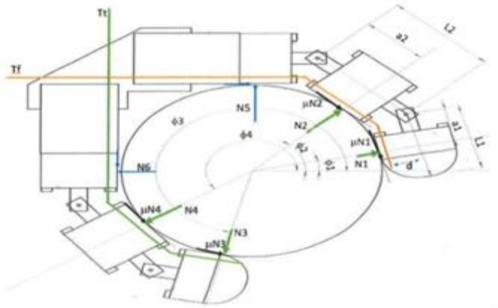

Figure - Finger and thumb holding a cylindrical object.

T_f = tension in finger tendon.; T_t = tension in thumb tendon
D = distance between tendon attachment point and pivot.
R = radius of link (link is cylindrical);
I = length of spring
μ = 1 coefficient of friction
x = compressed length of i^{th} spring
L_i = length of i^{th} link
Taking moment about joint 1

$$T_f d + N_1 a_1 + \mu N_1 r + N_2(L_2 - a_2) + \mu N_2 r + \frac{kx_1 l}{2} = 0$$

Taking moment about joint 4

$$N_4 a_4 + \mu N_4 r + \frac{kx_4 l}{2} = 0$$

3.2. Torque analysis

Torque at each joint of gripper can be calculated using the, Euler lagrangian formulation

$$\frac{d}{dt}\left(\frac{\partial k}{\partial \dot{\theta}_i}\right) - \left(\frac{\partial k}{\partial \dot{\theta}_i}\right) + \left(\frac{\partial k}{\partial \dot{\theta}_i}\right) = \tau_i$$

$$T_1 = d_{11}\ddot{\theta}_1 + d_{12}\ddot{\theta}_2 + h_{111}\dot{\theta}_1^2 + h_{221}\dot{\theta}_2^2 + (h_{221} + h_{121})\dot{\theta}_1\dot{\theta}_2 + c_1 + \tau d_1 + \tau s_1$$

$$T_1 = d_{21}\ddot{\theta}_1 + d_{22}\ddot{\theta}_2 + h_{112}\dot{\theta}_1^2 + h_{222}\dot{\theta}_2^2 + (h_{212} + h_{122})\dot{\theta}_1\dot{\theta}_2 + c_2 + \tau d_2 + \tau s_2$$

Two extra terms were added

$$\tau d_i = cd_i\dot{\theta}_i$$

Where cd = damping coefficient

$$\tau s_i = \sum_{i=1}^{n} \frac{1}{2} l^2 \sin\theta_i$$

Where n=2 for our design
So, for example joint 1

$$\tau s_1 = \frac{1}{2} l^2(\sin\theta_1 + \sin\theta_2)$$

And for joint 2 [25] [26] [27]

$$\tau s_2 = \frac{1}{2} l^2 \sin\theta_2$$

Where,
The medial joint of the finger is joint 1 and the distal joint of the finger is joint 2, and similar notation is used for thumb.

θ_i = joint angle of i^{th} joint,
τ_i = torque at i^{th} joint

We can ignore the terms which do not have significant effect, such as Coriolis terms and all the terms of inertia matrix except the diagonal terms. The torque can be written as [6] [28] [29].

$$\tau_1 = \alpha\tau\,;\ \tau_2 = \beta\tau$$

And

$$\tau = Td$$

Where T= tension in the tendon and d=distance between pivot and connection point of tendon phalanx. [6] [17] [18] [31]

Conclusions

This study focuses on the development of a kinematic model for a four-fingered dexterous robotic hand, designed for potential use in industrial and workplace environments, particularly for handling irregularly shaped or soft objects. The model incorporates four fingers, strategically configured to ensure secure grasping and effective manipulation. The design of joints, links, and other kinematic elements closely emulates the structure and functionality of the human hand. Simulation results demonstrate promising outcomes, supporting the feasibility of developing a functional prototype. The kinematic simulation was used to analyze the reachable workspace and evaluate the kinematic limitations of the proposed design.

Scope of Future Work

Torque analysis in multi-fingered robotic grippers holds significant potential across multiple dimensions of robotic engineering, including design, control strategies, and practical implementation. It is fundamental to improving the performance, reliability, and safety of robotic grippers in a wide range of industrial and service applications. Looking ahead, torque analysis will continue to evolve through a multidisciplinary lens, combining innovations in robotics, control algorithms, material engineering, and artificial intelligence. The progression toward more advanced and adaptive grippers is expected to unlock new possibilities in sectors such as manufacturing, logistics, healthcare, and other emerging fields.

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