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A note on conceptual models in robotics: A case study of modelling mechanical grippers using geometric and topological properties

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Abstract. In this study, the geometric and topological aspects of mechanical grippers are investigated. The main focus is on their mechanical behaviour during a precision pinch. Precision pinch is one of the fundamental grasping mechanisms. It occurs when the thumb and index finger come together to grasp small objects, dynamically altering the gripper's geometric and topological configuration. These localised geometric changes can affect force distribution, grip stability, and overall mechanical efficiency. A computer simulation was performed to quantify geometric and topological transformations during precision pinch and their impact on force trajectories. These trajectories were analysed in terms of geodesics on a torus, representing the shortest paths between two points on the fingers' surface. It was demonstrated that variations in gripper geometry influence mechanical force distribution and structural connectivity. Incorporating geometric and topological modelling into gripper design may lead to adaptable bionic devices. Furthermore, this method may help identify stress-prone areas, optimising force trajectories and stress pathways while addressing the limitations of existing models that oversimplify grasping mechanics.

Keywords: gripper; grasping; topological distance; ODE; Nemenyi theorem.

1. INTRODUCTION

Unlike previous studies, which primarily focus on kinematic control or optimisation algorithms, this work proposes a conceptual framework in which the force distribution emerges naturally from the geometric and topological properties of the gripper. Mechanical grippers are designed to grasp, hold, position, and orient objects. They are crucial for tasks such as assembly and material handling. Mechanical grippers function as the "hands" of robots, enabling interaction with the physical environment. This study investigates the intrinsic mechanical properties of gripper movements, particularly precision pinch. Rather than relying on external control signals or computationally intensive algorithms, this framework emphasises internal force distribution mechanisms. Unlike conventional models that treat the hand as a static system, this framework takes into account the dynamic nature of hand movements. A potential advantage of this framework is its ability to address force determination challenges in overconstrained systems, similar to hyperredundant mechanisms such as elephant trunk robots [1]. These systems, which feature high degrees of freedom and complex segment interactions, face challenges in distributing forces efficiently [2]. Traditionally, such control problems are solved using optimisation techniques that balance energy expenditure and stability [3, 4]. However, these methods often rely on intricate inverse kinematics and iterative computations.

By grounding the force distribution in geometric and topological principles rather than predefined control rules or configurations, this approach may be applicable to a range of pinch and grasp types. The method's ability to adapt force trajectories along geodesic paths may suggest potential robustness to different grasping strategies, such as lateral pinch, key pinch, or power grasps. Additionally, accounting for local geometric variations in the gripper-object interface may contribute to efficient force application across different grip configurations. Even in the presence of external perturbations, the geodesic-based optimisation framework could help maintain stable force trajectories, minimising stress concentrations. Understanding stress pathways and geometric adaptations in gripper movements could also improve durability.

Conceptual models are used to communicate the system's functionality and structure to stakeholders. They are high-level representations of a system (see Fig. 1). The model is an abstract representation of the results from reality. The conceptual (or logical) model depicts what a system is or does. The implementation model is a technical representation (usually less abstract

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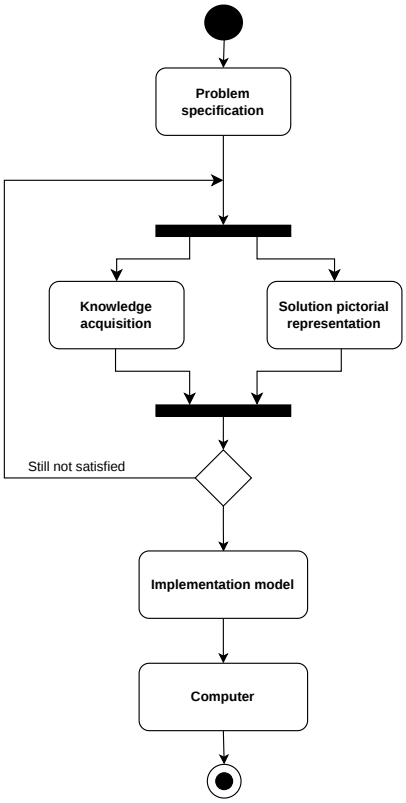

Fig. 1. Activity diagram of a generic conceptual model

than the conceptual model) of how the system is implemented. Popular synonyms are the implementation model and the technical model. The primary objective of a conceptual model is the representation of the fundamental principles and basic functionality of the system. It must provide an easily understood system interpretation for the system developers. According to [5, 6], a conceptual model, when properly implemented, should satisfy four fundamental objectives.

1. Enhance an individual's understanding of the representative system.
2. Facilitate efficient conveyance of system details between stakeholders.
3. Provide a point of reference for system designers to extract system specifications.
4. Document the system for future reference and provide a means for collaboration.

Conceptual models help clarify the core principles and behaviours of the system [7]. They create a basis for further development and implementation. The human hand, a paradigmatic example of a mechanical system, provides a compelling subject for study due to its accessibility and the availability of non-invasive, cost-effective methodologies. More on the subject can be found in [8].

Advances in hand mesh reconstruction algorithms and kinematic models utilise precise three-dimensional representations of the hand in various poses [9]. Additionally, combining marker-based motion capture with deep learning-based hand mesh reconstruction facilitates the estimation of contact regions between the hand, fingers, and object surfaces [10, 11]. This study focuses on understanding how local geometric variations (e.g., shape, size, and form) during grasping produce detectable mechanical effects. Central to this analysis is the application of topological principles, particularly the classification of shapes based on connectivity and topological "holes". For example, a sphere without holes (genus 0) differs fundamentally from a torus with one hole (genus 1) [12]. In this paper, geometric and topological aspects are integrated to describe gripper mechanics. We argue that temporal geometric variations significantly impact the force distribution, while topological modelling serves as a link between mechanics and structural analysis, offering a comprehensive understanding of grasping dynamics.

Agile software development is a flexible project management approach focused on a short software development cycle. It advocates continuous software improvement and ongoing teamwork. It contrasts with a rigid, step-by-step classic software design and implementation method. However, these agile software development principles are only applicable to the implementation (not conceptual) models. Implementation (or physical) models are not part of this research.

The objectives of this study are threefold. First, we seek to identify localised geometric and topological changes in the hand during precision pinch – a fundamental grasping action involving the thumb and forefinger – and their effects on force trajectories. Second, we develop mathematical (conceptual) models that enable predictions of mechanical performance. Third, we address the limitations of existing approaches and explore how our insights can inform the development of the next generation of bionic devices.

2. GEOMETRY AND TOPOLOGY OF GRASPING

Gripper mechanics provide a paradigmatic example of how geometric configuration affects movement. The hand consists of a stable wrist and at least two fingers that can oppose each other to generate force [13]. The thumb, a unique feature of humans and higher primates, accounts for approximately 40% of hand function [14, 15]. The motor, sensory and mechanical characteristics of the hand are closely correlated, allowing for a wide range of actions [16]. However, the ability of the hand to adapt to different positions and apply appropriate mechanical forces is crucial to recovering from injuries and surgeries [14]. Regarding mechanical movements, the basic functions of the hand include various types of grasps, classified in several ways [17, 18]. The main types of grasps include (Figs. 2A–G):

1. Precision pinch (or terminal grip, palmar grip, fingertip-to-fingertip): The fingertips come together to grasp small objects, such as a pen.
2. Lateral or opposing grasp: The thumb opposes laterally to generate greater force, for example, when holding a ticket.
3. Key grip: Requires stable support of the index finger and is used to hold a key.
4. Cylindrical grip (or chuck grip): Allows wrapping around small cylindrical objects by joining the thumb, index, and middle fingers.
5. Hook grip: Used to lift a suitcase or bag.

6. Spherical grip: Used to grasp a ball.
7. Power grip: Used for movements such as holding a stick or a bat.

Another classification of grasps is based on the grip strength [18, 19]:

1. Precision grip: Characterised by thumb abduction or opposition. In this grip, the hand assumes a dynamic position and includes grips 1–4 listed above.
2. Power grip: The adductor pollicis stabilises the object against the palm. In this grip, the hand is in a static position and includes grips 2, 5–7. Grip strength tends to decrease with age [20].

Among these, we focus on the precision pinch, as it represents the most fundamental and minimal form of grasping, providing a conceptual model for analysing gripper mechanics. In this grasp, one finger remains stationary while the other moves against it [13], generally involving the thumb and index finger to manipulate small objects with precision. The movement of the gripper during a precision pinch induces localised geometric changes, thereby influencing the distribution of forces (Fig. 2H).

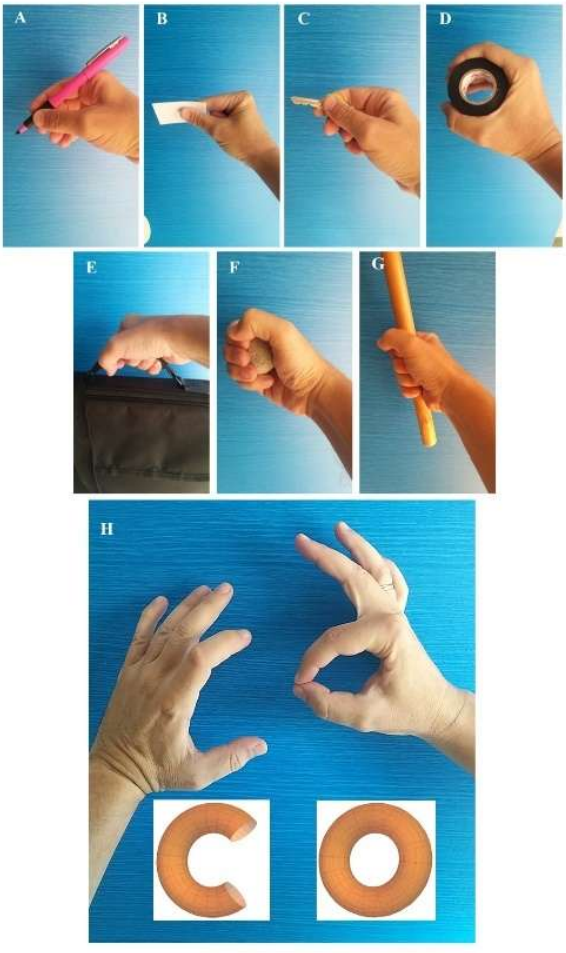

Fig. 2. Geometry of hand grasping: A–G: Basic types of prehension as defined by [17, 18] and [14]. See the text for the nomenclature and further details; H: Two human hands before and after a precision pinch made with the thumb and forefinger. The change in configuration affects the geometry of the hand

To understand this distribution, available conceptual models can be used to describe how force is applied across different points in space.

The total force exerted by the gripper can be broken down into components along three perpendicular directions. The way forces are distributed across the gripper surface can be represented by a continuous function that considers the central point of the grip and how the force spreads in different directions. In addition, the internal stress generated by these forces depends on how the force is applied and on the material properties of the gripper. To analyse internal forces, the concept of a stress tensor can be used, which represents how force is distributed within the hand's tissues [21, 22]. The hand, being a deformable body, follows certain equilibrium principles, ensuring that external forces and moments remain balanced. The response of hand tissues to applied forces depends on their material properties, which do not always follow simple elastic behaviour. Instead, biological tissues exhibit viscoelastic properties, which means that their response changes over time under varying loads [22]. To realistically describe how soft tissues behave dynamically, a set of equations is required that incorporate viscoelastic and nonlinear deformation effects to capture how forces and stresses evolve over time [23, 24]. This modelling approach enables the calculation of the force distribution on the surface of the gripper, how these forces translate into internal stresses, the dynamic behaviour of the gripper during grasping, and the time-dependent nature of tissue deformation.

Flows and paths occurring on a three-dimensional manifold (such as a 3-ball) differ significantly from those on a donut-like solid torus. For instance, when studying the propagation of sound waves or the viscoelastic attenuation of shear and longitudinal waves in isothermal and thermal fluids, the non-uniform curvature of the torus requires a distinct spectrum of eigenfrequencies and their corresponding basis functions, unlike planar geometries [25]. A continuous manifold can be described as a three-dimensional continuous space, while a solid torus is characterised by a central axis with a vortex at each end and a coherent field surrounding it. Energy flows through one vortex along the central axis, exits through the other vortex, and wraps around itself to return to the first vortex. Toroidal structures exhibit unique characteristics, such as the simultaneous presence of positive, zero, and negative Gaussian curvatures within the same system [26]. Trajectories in a torus can be described in terms of geodesics, the shortest lines between two points on the surface [27]. A useful approach to mathematically describe geodesics in a torus is to consider them as paths traced over time by the movement of a point on the surface, with the parameter identified with time itself [21, 28]. Geodesics are fundamental for understanding the force distribution during grasping (Fig. 3). We argue that during precision pinch, the applied force trajectories may align with geodesics on the manifold defined by the gripper-object interface, minimising energy expenditure and maximising mechanical efficiency. Neményi's Theorem can further enhance this geodesic-based approach by establishing a connection between isothermal curves and planar stress systems, providing a robust mathematical framework for predicting stress trajectories in elastic materials.

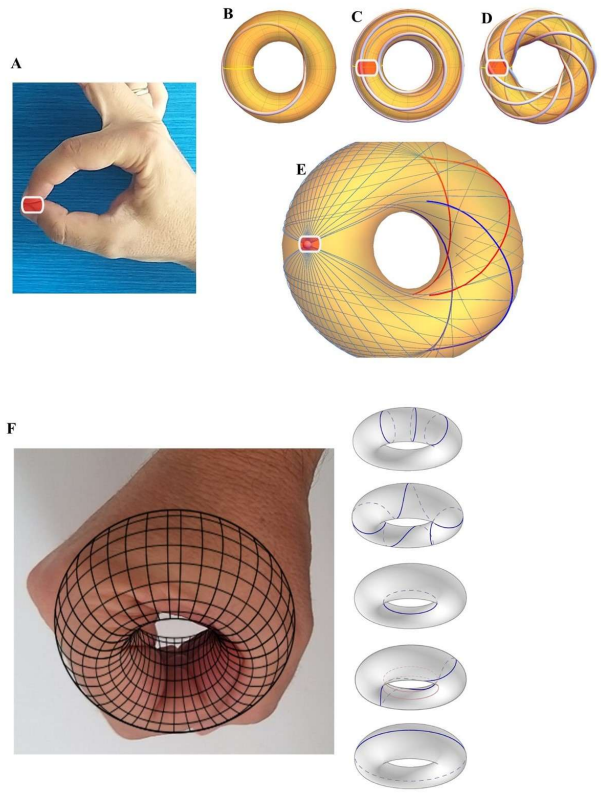

Fig. 3. Different paths of geodesics that move across the surface of a torus. A geodesic on a torus is a curve on the toroidal surface that may wind multiple times, forming loops around both the longitudinal axis and through the central hole. Modified from [30]. A–E: Two sets of geodesics emanating from a "base point" – in our case, the contact point between the thumb and forefinger – are shown and plotted for a distance corresponding to a given radius (thin curves). The two sets of geodesics focus along curves called conjugate loci, whose components are depicted as either heavy red or blue curves. As the geodesics approach the inner equator of the torus, the conjugate points move farther apart, and the resulting geodesic pattern on the torus surface becomes increasingly complex. Modified from [31]; F illustrates the different families of geodesics that take place in the toroidal structure formed by the pinch. Modified from [32]

3. SIMULATING HAND DYNAMICS THROUGH GEOMETRIC AND TOPOLOGICAL PRINCIPLES

The transition from standard force, stress, and strain equations to the topological framework relies on abstracting the mechanical properties of the hand during grasping into a broader geometric and structural perspective. The mathematical approach begins with the equilibrium equations for deformable bodies, where the sum of forces and moments is zero. These are complemented by constitutive models, such as Hooke's law, which connect stress to strain through the stiffness tensor. The stress tensors capture the internal force distribution, while the strain quantifies the corresponding deformation. The spatial complexity of these interactions is often modelled as a force field, expressed as a continuous function of coordinates. As the hand transitions through different configurations during grasping, the distribution of stress and strain reveals emergent structural features. These features can be abstracted as a continuous manifold, where the force trajectories naturally align along geodesics. In this context, geodesics represent the shortest paths of mechanical energy flow across the gripper-object system. The relationship between stress and geodesics is formalised in continuum mechanics, where stress trajectories correspond to isothermal curves described by the equilibrium equations [29]. For instance, in a planar elastic system, these curves are solutions to differential equations balancing the stress components in Cartesian coordinates.

The study moves to topology by focusing on the large-scale properties of these stress pathways rather than their precise values. For example, a hand at rest can be modelled as a genus-zero manifold without holes resembling a sphere-like structure. During a precision pinch, the dynamic contact between the thumb and forefinger introduces localised voids or "holes" in the geometry of the gripper-object interface, representing topological transformations that alter the system's genus. The connection between mechanics and topology becomes evident when stress trajectories are analysed as a network. In this framework, critical stress points, such as high-stress regions, are treated as nodes, whereas geodesic paths form edges connecting these nodes. The network evolves as forces are applied and undergoes topological transitions such as the creation of loops or the merging of pathways. The localised voids and pathways formed during grasping reveal how the gripper redistributes mechanical energy efficiently. By incorporating the large-scale connectivity and void formation observed in the gripper-object system, our approach captures the emergent properties of the force distribution during grasping.

A numerical simulation was conducted to evaluate whether geodesic principles improve force distribution and grip efficiency. The study modelled precision pinch involving the thumb and index finger and examined optimisation of force application through geodesic-based adjustments. The simulation was structured to compare conventional force distribution with geodesic-optimised force trajectories. A gripper model was created, focusing on a single finger's length to represent the interaction between the thumb and index finger during a precision pinch. The simulated finger was modelled as a curved structure, discretised into 100 points, each corresponding to a spatial position along the finger length of 10 cm. The force application was concentrated at these points, with the total applied force modelled as a Gaussian function centred at the middle of the finger length, representing a natural grasping force profile. The maximum force was set at 15 N. The force width parameter was set to 1.5 cm. The contact area was set to 0.5 cm. The initial force trajectory was assumed to follow a linear function, evenly distributing the applied force along the finger. However, this does not align with the natural mechanical structure of a gripper, leading to excessive force in certain regions and instability during grasping. A numerical optimisation algorithm based on geodesic curvature was applied to optimize force distribution. The objective of the optimisation was to minimise the discrepancy between the applied force and the natural force trajectory along the geodesic paths of the surface. The initial guess for the optimisation was a linear force application ranging from 0 to 15 N. A quasi-Newton method, implemented using the

BFGS (Broyden-Fletcher-Goldfarb-Shanno) optimisation algorithm [33], was used to refine the force trajectory. The resulting optimised force path showed a smoother distribution, reducing peak stress areas and balancing the force applied along the finger.

The simulation was implemented in Python, using NumPy for array manipulation, mathematical operations and numerical calculations. SciPy's BFGS optimisation algorithm was applied to minimise force deviation and compute an optimised geodesic-based force trajectory. Data visualisation was carried out using Matplotlib to compare the conventional versus optimised force distribution along the gripper.

The total force applied during a grasp is modelled using a Gaussian function:

$$F(x) = F_0 e^{-\frac{(x-x_0)^2}{2\sigma^2}}. \tag{1}$$

For F_0 the maximum force, x represents the position along the contact region, x_0 is the centre of force application, and σ is the width parameter controlling force distribution.

This function models how the force is naturally distributed during a precision pinch. Stress σ is defined as:

$$\sigma = \frac{F}{A}, \tag{2}$$

where: σ is the stress (in N/m^2), F is the applied force (in Newtons), A is the contact area (in m^2).

As the gripper transitions through different configurations during grasping, the distribution of stress and strain reveals emergent structural features. These features can be abstracted as a continuous manifold, where force trajectories naturally align along geodesics. In this context, geodesics represent the shortest paths of mechanical energy flow across the gripper-object system. The relationship between stress and geodesics is formalised in continuum mechanics, where stress trajectories correspond to isothermal curves described by equilibrium equations.

The optimisation process involves defining a cost function:

$$C(T) = \int T(x)\,\mathrm{d}x, \tag{3}$$

where $C(T)$ the cost of force application over the trajectory $T(x)$ is quantified.

The energy function E is given by:

$$E = \sum_{i=1}^{n} F_i\,, \tag{4}$$

where F_i are the individual force components contributing to the total force.

Numerical optimisation was performed using SciPy's minimise function to adjust force trajectories according to geodesic paths. Numerical optimisation was performed using the Sequential Least Squares Programming (SLSQP) algorithm implemented by using SciPy's optimize.minimize function. The

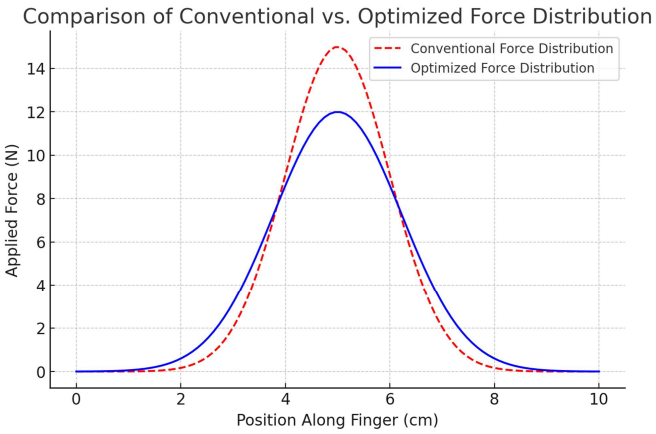

Fig. 4. Comparison of conventional vs. optimised force distribution. The figure illustrates the difference between conventional and geodesic-optimised force distribution along the length of a finger during a precision pinch. The red dashed line represents the conventional force distribution, which exhibits a higher peak stress concentration around the central contact point. This uneven force application can lead to instability and excessive pressure in localised regions. The solid blue line shows the optimised force trajectory, which follows geodesic paths, resulting in a smoother distribution of applied forces. This reduces the areas of maximum stress and improves grip stability. The x-axis indicates the spatial location along the finger where force is applied during grasping, while the y-axis represents the magnitude of force applied at different positions along the contact region

procedure minimised the squared deviation between the discretised force distribution and the prescribed target profile, subject to conservation of total force and pointwise force bounds. Geodesics provided the geometric framework for interpreting configuration-dependent force pathways, while the constrained optimisation operated directly on the discretised force profiles used in the simulations. The optimisation aimed to align the applied forces with the natural mechanics of grasping, leading to a significant reduction in the localised stress peaks. The improvement in force efficiency was quantified using the equation:

$$E = 100\left(1 - \frac{\sum F(x)}{\sum (F(x) - T(x))}\right), \tag{5}$$

resulting in an overall improvement in efficiency of 17.8%.

Our numerical simulation confirmed that geodesic-based force optimisation can significantly improve gripper design by improving grip efficiency and stability – see Fig. 4. A 17.8% increase in force efficiency demonstrates the method's effectiveness in optimising force trajectories. The topological analysis of stress trajectories allows engineers to address potential failure points. By reinforcing areas prone to high stress or optimising the arrangement of materials to follow geodesic paths, the gripper may improve device durability. By aligning force distribution with geodesic paths, the gripper may achieve smoother grip transitions, reducing energy dissipation and enhancing user comfort. Dynamic adjustment to varying grip strengths and object geometries may make grippers more adaptive to real-world conditions, since stabilised grasping may minimise excessive

pressure points and decrease the likelihood of slippage. A potential benefit of geodesic-based optimisation is its ability to address excessive localised pressure, a common issue in conventional grippers, leading to discomfort and inefficient energy transfer. By distributing the forces more evenly, our method may increase durability and wearability. Additionally, geodesic-based force optimisation may enable grippers to adjust grip strength in real-time to different object geometries, ensuring intuitive interaction in fine motor tasks.

4. CONCLUSIONS

Conceptual models operate at a higher level of abstraction than implementation or technical models. They are constructed without redundant details, constraints, specific parameters, and initialisation conditions to create a "big picture". The higher abstraction level allows designers to discover more solutions or solutions of better quality, since higher abstraction does not restrict the search for more general solutions. Needless to say that conceptual models are of fundamental importance when the "code-and-fix" approach is practiced by software developers. Implementation models include details such as tolerance levels, iteration limits, and stopping criteria for the optimisation algorithms and heuristics. In the presented case, implementation models should incorporate sensor technologies to measure force trajectories in real-world grasping tasks [34, 35]. In software development, one of the first problems is the highest level of a conceptual model for a business problem solution selection. It can be done by a bespoke solution (understood as a product, service, or strategy built completely from scratch to fit the exact needs of one specific person or business) or by in-house software development. Both of them have advantages and disadvantages and for an implementation model of it a pairwise comparisons method could be used (as one of many existing multi-attribute decision-making methods) [36].

In this paper, a numerical methodology by adopting constrained SLSQP optimisation with an explicit objective function, force-conservation constraint, and pointwise bounds was refined. In the proposed conceptual framework, the force distribution emerges from the topological and geometric properties of the gripper and dynamic nature of hand movements. Thanks to simulations it was possible to give final results where the difference between conventional and geodesic optimised force distribution along the length of a finger during a precision pinch are shown. In the conventional approach, a higher peak force stress concentration around the central contact point is seen. But as a negative consequence, uneven force can lead to instability and excessive pressure in localised regions [37]. In the proposed approach, a smoother distribution of applied forces is seen. It reduces the areas of maximum stress and system instability.

Future work should define the constraints applied to force trajectories, the mathematical formulation of geodesic-based force adaptation, and parameters governing initial force distribution. For example, the Gaussian force profile used to simulate natural grasping should specify values such as its mean, variance, and the function governing the stress tensor. Expanding this model to account for multi-finger interactions and more complex hand movements would also be a valuable direction [38]. The focus here is on precision pinching as a fundamental grasping action. Applying these principles to a wider range of grip types may require further refinement of the modelling approach.

Grasping is a fundamental mechanism of holding things in hands. Precision in grasping small objects contradicts with dynamical altering the gripper's geometry for heavy objects. This could be a very challenging process. Since most people possess two hands, future research could also investigate the pairwise comparisons method (for details, see [39–41]). Turning left or right, going up or down, increasing or decreasing movement speed are only a few examples of pairs involved in decision making by robots. This can be especially crucial for autonomous humanoid robots [42]. Their adaptation to dynamic environments can be essential for artificial agents aiming to collaborate with people interactively. A social humanoid robot can adapt its behaviour to different users and may produce a more successful interaction.

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Declarations

Ethics approval and consent to participate: This research does not contain any studies with human participants or animals performed by the Authors.

Consent for publication: The Authors transfer all copyright ownership in the event the work is published. The undersigned authors warrant that the article is original, does not infringe on any copyright or other proprietary right of any third part, is not under consideration by another journal, and has not been previously published.

Availability of data and materials: all data and materials generated or analysed during this study are included in the manuscript. The authors had full access to all the data in the study and took responsibility for the integrity of the data and the accuracy of the data analysis.

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