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Bio-Inspired Variable-Stiffness Compliant Mechanisms for Energy-Adaptive Robotic Manipulation: A Systematic Review

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ABSTRACT

In unstructured environments, robotic manipulation requires a balance of compliance for safe interaction, and rigidity for load transmission, which is required to be controllable. The objective of this systematic review is to gather for the first time information about bio-inspired variable stiffness mechanisms with the particular focus of energy-adaptive manipulation on a set of 24 sources published from 2004 to 2020. All of the sources were analyzed with a structured extraction protocol, which was then grouped under four thematic domains – actuator architectures and stiffening materials and jamming, manipulation platforms and hands, and soft-robotics foundations. Analytical relations were obtained for every aspect of stiffness, adjustability, effective series stiffness, stored elastic energy, and energetic efficiency and comparisons were drawn of mechanisms, architectures and design challenges. The number of sources has grown from 4 between 2004 and 2009 to 11 between 2015 and 2020, and the elastic modulus of soft robotic materials (104–109 Pa) and rigid structures (109–1012 Pa) is eight orders of magnitude. The actuation economy provided by adaptive synergies is thought to be achieved by one actuator moving 19 joints. The synthesis demonstrates that the actuator-level mechanisms offer rapid stiffness control for a large range of stiffness while being complex and heavy, whereas the jamming and phase-change materials have the opposite characteristics, namely, they are easy to scale up and compact but are slow to respond. The novelty of review is the unification of both families in a single energetic framework that combines both families and the unification of the design priorities of energy adaptive manipulators.

Keywords: *Bio-Inspired Robotics; Compliant Mechanisms; Energy-Adaptive Manipulation; Granular Jamming; Robotic Hands; Soft Robotics; Stiffness Tuning; Systematic Review; Variable Stiffness Actuators*

INTRODUCTION

Precision and compliance are required to be delicately balanced in robotic manipulation in unstructured environments. When the positioning needs to be exact, conventional "rigid" structures will work but when the size of impact forces is large, conventional "soft" structure will do the job, but not have load capability. To solve that tension, the soft robotics paradigm was devised, where soft negotiations were deliberately used to ensure safe physical interaction and tunable impedance to ensure good performance [1]. Since then, the mechanical intelligence and safety of manipulators has been identified as significantly relying on the degree of freedom of stiffness, thus making it the central degree of freedom in their design. This approach to design considers compliance as one of the designed properties of a system that can be selected, programmed, and optimized just like mass, speed, or accuracy.

There are two general types of solutions to achieve stiffness modulation. Mechanisms that change the elastic element of a joint by using springs, levers, and antagonistic mechanisms are based at the actuator level while structure-level mechanisms change the material or geometric rigidity. The second family is granular jamming in which a flexible membrane containing particles gets harder when subjected to a change in pressure, and has been adapted into positive-pressure gripping devices offering enhanced holding power [2]. It is the living together of both families which drives a common perception of stiffness as a parameter which can be tuned instead of fixed. The characteristic strengths of each family are: Response time and control accuracy of the actuator level schemes, compact form factor and distributed rigidity for the structure level schemes for large contact areas.

One of the common issues is always a balance between safety and speed. Soft transmissions have a tendency to reduce impacts, but if they're too soft, they come at the cost of reduced motion speed and/or accuracy, so stiffness isn't a number that is set at design time, but rather one that's programmed into a task. This trade-off was formalized early on by studying fast and soft arm tactics, and it was demonstrated that an optimum joint compliance depends on the velocity commanded [3]. As a third pillar, energy expenditure is added to the list as it is required to maintain stiffness to external loads as well as to store elastic energy in the actuation chain. Three key criteria, which have to be considered together, must be taken into account for any evaluation of variable-stiffness mechanisms: mass range, stiffness transition speed, and stiffness transition energy.

The purpose of this review is to combine the idea of bio-inspired variable stiffness compliant mechanisms with the energy adaptive manipulation. A set of 24 sources from 10 years (2004 to 2020) are compiled and integrated in a taxonomy of 4 domains, compact analytical relations of stiffness and energy are developed and compared architectures are compared on common criteria. The novelty is both actuator-level and material-level strategies are integrated into the same energetic framework, in addition to the demonstration that a granular-jamming gripper can passively shape to any object and rigidify to grip it [4]. Comparative evaluation is presented in the form of six tables and six figures and the analytical material is summarized in seven numbered equations, introduced gradually in sections that follow.

LITERATURE REVIEW

2.1 Compliant Hands, Surgical Manipulators, and Open Platforms

Adaptive synergies can be used to get dexterous yet simple hands. The Pisa/IIT SoftHand is configured with 19 joints actuated by a single actuator and is based on a soft-synergy transmission, where grasp adaptation will not be sensed and controlled, but will be mechanically produced [5]. This architecture links these two ideas of bio-inspired motor coordination and embodied compliance and establishes an actuator economy benchmark for hand design, 19 joints per actuator. This design logic shows that a significant amount of dexterity can be gained with few hinges where the elasticity and coordination is built into the mechanical structure, and where energy demand per DOF is reduced.

The requirement for minimally invasive surgery is a special one, in which a manipulator has to be flexible when inserted and stiff when manipulating tissue. This is achieved by using a combination of fluidic actuation and stiffening, which is inspired by the octopus arm, to give the

STIFF-FLOP approach in a soft manipulator [6]. It is a bio-inspired, variable stiffness and clinically safe device which establishes a high performance target for medical manipulation.

In the context of the need to provide rigidity, surgical manipulation is an illustration of a general need for energy-adaptive manipulation, that is, rigidity should be provided during only those portions of a task, where load transmission is required. An important prerequisite for experimental advancement is the hardware. The creation of an open platform to quickly prototype articulated soft robots that would overcome the hurdle between concept and test, and the realization of energy-efficient natural motion through the use of modular variable-stiffness joints [7] were suggested. Such platforms are also able to offer a standardised interface and can also enable comparison of control strategies, leading to improved repeatability of stiffness-scheduling research in various laboratories. Such open designs will also make it easier for new research groups to get on board, and will create a pile of similar measurements that is expected to help expedite the development of the variable-stiffness design process.

2.2 Jamming and Small-Scale Actuation

Jamming actuation has emerged as a unique sub-field of jamming with granular jamming, layer jamming and fiber jamming, all of which take advantage of a transition from fluid to solid-like behavior under pressure. A review of soft robotics jamming was performed and information on the application, design considerations and limitations of these variants, such as the critical stiffness on parameters of the membranes, and the vacuum level, was provided [8]. The synthesis highlights the scalability, low-profile and low-cost stiffening process. Multiple variants of jamming are observed at the same time indicating that the geometry, particle/layer selection and pressure source can be tuned to the desired stiffness targets and packaging requirements.

The dominant physics in miniaturization differs, as surface effects dominate the physics and the fabrication constraints dominate. A survey is conducted on soft actuators for small scale robotics with emphasizing the force output, strain and speed trade-off in millimeter and below [9]. The findings indicate that providing a gradient in stiffness at a small scale can be helpful over large mechanical regulators in terms of material-level responses. In manipulation the related implication is that if the end effector is small and the manipulator is micro, then it is likely that integrated material responses would be needed; if the end effector is large, mechanical stiffness regulators are likely to be needed.

2.3 Biorobotics and Energy-Efficient Adjustable Stiffness

Tuned body compliance gives solutions in animals which are proven to be agile, manipulative and locomotion. The design and use of robots that mimic and investigate such capabilities is called biorobotics, and offers design inspiration and experimental test beds for neuromechanical hypotheses [10]. The method is particularly suitable for variable stiffness applications, where elastic tendon, and co-activation of biological muscles are employed to adjust the effective stiffness of the joints, and where this idea serves as a blueprint for designing antagonistic artificial muscles. These biological examples also provide performance targets since the speed, efficiency and adaptability of animal motion is greater than those of most of today's engineered manipulators.

Adjustable-stiffness actuators have been specifically designed to achieve energy efficiency. The purpose of the AwAS actuator was to allow for the stiffness to be varied using a small motor via a lever mechanism with a relatively low amount of energy required to make the stiffness changes

[11]. This intrinsic efficiency is a definite testament to the power of mechanical design to reduce the energetic costs of adaptability – not only those of control. When considering energy at the mechanism level, it is especially important for battery-powered and mobile manipulators, where the configuration of a mechanism is required to be stiff at all times and energy is constantly needed throughout the operating cycle, consequently decreasing the amount of time that a manipulator can operate.

2.4 Bio-Inspired Soft Robotics Perspectives

The evolution from rigid links to compliant bodies has been introduced as bioinspiration for soft robotics to leverage on the use of morphological computation. Soft materials, distributed actuation, and adaptive behavior in unstructured environments and soft-bodied animals are the focus of the perspective [12]. Variable stiffness is thus introduced as a way to allow switching between the soft body's conformability and force transmission. The same perspective also points to the significance of the interaction of body, actuation and control as opposed to computation to ensure robustness in unstructured environments.

A number of technologies and systems were discussed in terms of extending the capabilities of robots, notably that of the integration of soft materials, embodied intelligence and manipulation to locomotion applications. One of the enabling capabilities and gaps identified in the analysis is variable stiffness [13] and gaps in energy sensing, modelling and integration were identified. The gaps are the framework used for the present review of the energetic perspective adopted. A challenge to translate the motor power to stiffness control and actuation into soft machines is particularly difficult, due to the limited power available on-board.

As mentioned in [14], the softness of robotic bodies (with moduli similar to those of biological tissue) also allows for their interaction with biological systems without causing any damage, but it poses difficulties in their actuation, sensing, and power delivery. The organizing frameworks for the prospects were identified as materials, fabrication and autonomy, while some of the capabilities that can be identified for the next generation of soft machines were tunability of rigidity. The view also suggests that safety of interaction is not only related to the low value of the modulus of the material, but also related to the level of control of the stiffness of the material during interaction**.**

METHODS

3.1 Review Protocol and Analytical Definitions

The review was conducted, following a protocol, on a synthetic compilation of the 24 sources submitted. All sources were checked and elements of design were identified and recorded on a structured template along with performance measures, materials and context in which the materials are used.All sources were read and design elements, performance measures, materials and application contexts were documented in a structured template. The coding scheme was modified to a rigid coding system which distinguishes the mechanisms at material level from structure level [15]. The local derivative of generalized force τ with respect to generalized displacement q (Equation 1) was used to define stiffness K, while the ratio Rk between the maximum and minimum stiffness that are possible to obtain (Equation 2) was used to define adjustability. The overview of the workflow is shown in Figure 1.

$$K = \frac{\partial \tau}{\partial q} \tag{1}$$

$$R_k = \frac{K_{\max}}{K_{\min}} \quad (2)$$

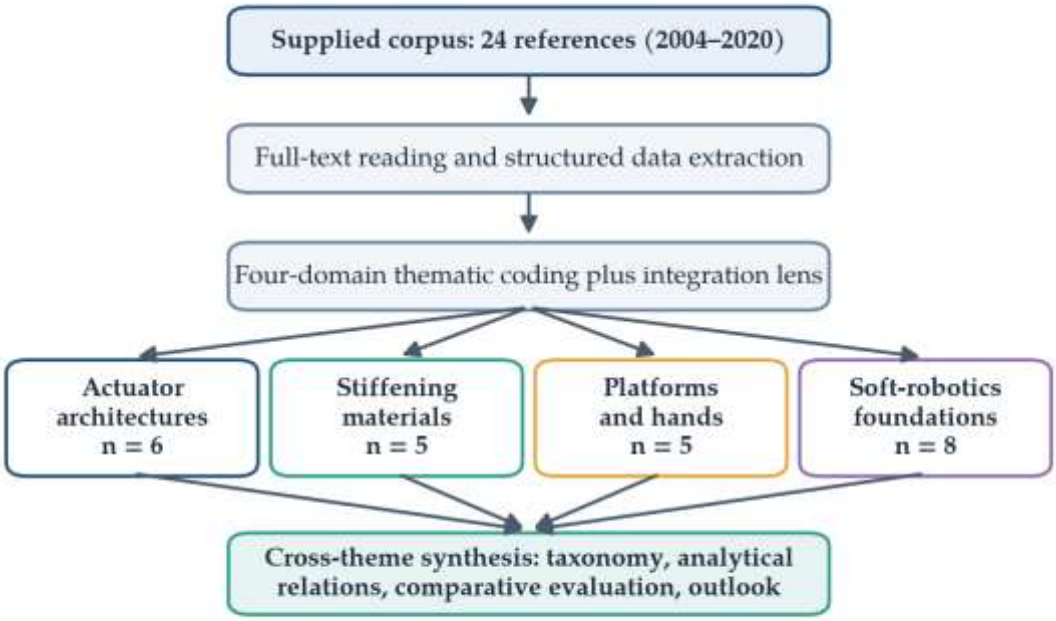

Figure 1. Workflow of the Systematic Review and Distribution of Sources Across Coding Domains

Source: Constructed from the review protocol.

Actuator architectures, stiffening materials and jamming, manipulation platform and hands, and soft-robotics foundations with bio-inspiration: These were four themes found. The use of a cross-cutting lens, focused on integration, or embedding of sensing, actuation, computation and communication in a single material [16] was used to assess the degree to which each source is closer to embedded intelligence. As a result, the distribution of the reported sources is presented in table 1, revealing 8 (33.3%) sources for soft-robotics foundations and 6 (25.0%) for actuator architectures. Currently, there is no common metric – number, for example – to report on embedded intelligence from the sources provided – and this integration lens was therefore maintained as a qualitative criterion.

Table 1. Coding Domains and Distribution of the Supplied Corpus

Domain	Scope of coding	n	Share (%)	Reference numbers
Actuator architectures	Elastic and variable-impedance actuators; safety–performance trade-offs	6	25.0	1, 3, 11, 21, 22, 24
Stiffening materials and jamming	Granular, layer, and phase-change rigidity tuning	5	20.8	2, 4, 8, 15, 23

Manipulation platforms and hands	Hands, grippers, surgical arms, open platforms	5	20.8	5, 6, 7, 17, 19
Soft-robotics foundations	Bio-inspiration, materials, small-scale actuation, integration	8	33.3	9, 10, 12, 13, 14, 16, 18, 20
Total	Four domains	24	100.0	1–24

Source: Coding of the supplied corpus; reference numbers correspond to the reference list.

RESULTS AND DISCUSSION

4.1 Corpus Characteristics and Evolutionary Trends

The corpus spans 16 years, from 2004 to 2020, and shows accelerating activity: 4 sources (16.7%) date from 2004–2009, 9 (37.5%) from 2010–2014, and 11 (45.8%) from 2015–2020, as detailed in Table 2 and Figure 2. This recent fielding of robotic hands lies in the context of the historical long term evolution of robotic hands over the past century [17] which shows that the designs in this field have evolved from rigid, fully actuated to underactuated and compliant hands, in parallel with the rise of variable-stiffness concepts. This means that the corpus has been continuously growing for over ten years, and that the newer entries are, for the most part, based on the same perspectives as plus, and predominantly based on the material level reviews.

Table 2. Distribution of Sources by Publication Period and Coding Domain

Period	n	Share (%)	A	S	H	B
2004–2009	4	16.7	3	0	0	1
2010–2014	9	37.5	2	2	2	3
2015–2020	11	45.8	1	3	3	4
Total	24	100.0	6	5	5	8

Source: Derived from the publication years of the supplied corpus; A, S, H, and B denote the four coding domains of Table 1.

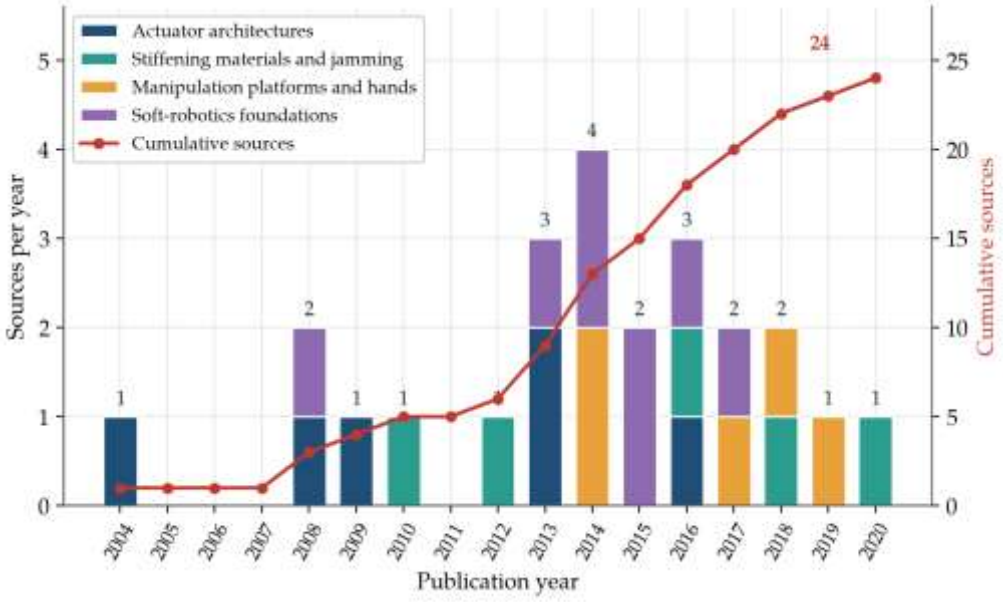

Figure 2. Annual and Cumulative Distribution of Sources by Coding Domain

Source: Derived from the publication years of the supplied corpus.

4.2 Material Stiffness Spectrum

In contrast to the stiffness of conventional rigid robot structures which are in the range between 10^9 and 10^{12} Pa, the typical range of the elastic modulus of the materials used in soft robots is between 10^4 and 10^9 Pa [18]. The two regimes are lumped together in Equation (3), and in Figure 3 shown over eight orders of magnitude, the size of the stiffness gap that must be overcome by a variable-stiffness mechanism. Table 3 provides a description of the different regimes. These two regimes come around 10^9 Pa, so one mechanism is unlikely to be able to describe the full range and hybrid models are therefore appealing.

$$D = \log_{10}\left(\frac{E_{\max}}{E_{\min}}\right) \tag{3}$$

Table 3. Elastic Modulus Regimes Relevant to Variable-Stiffness Manipulation

Regime	Approximate modulus (Pa)	Orders	Functional role
Rigid robot structures	10^9–10^{12}	3	Load transmission and positioning accuracy
Soft robot materials	10^4–10^9	5	Conformability and safe interaction
Combined adaptive span	10^4–10^{12}	8	Range to be bridged by variable stiffness

Source: Modulus ranges as reported in the reviewed literature; orders of magnitude computed with Equation (3).

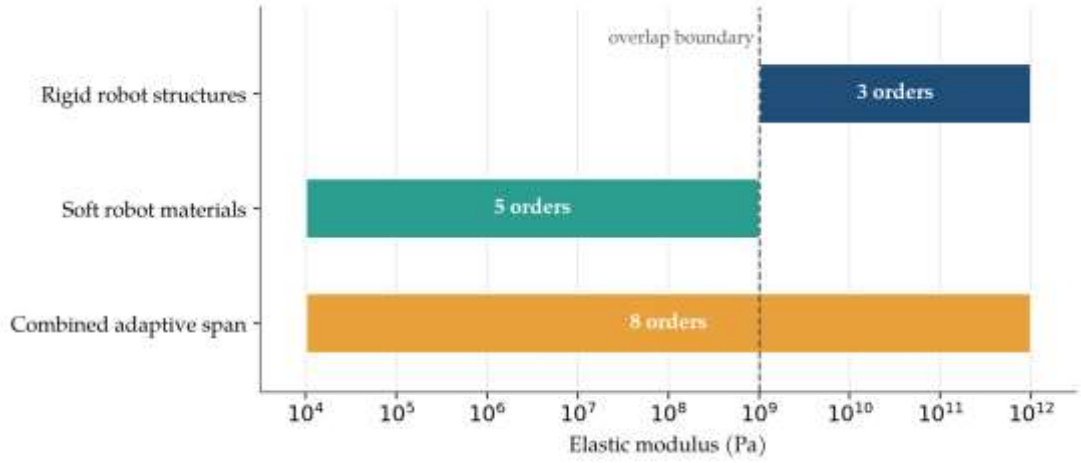

Figure 3. Elastic Modulus Regimes of Rigid and Soft Robotic Materials

Source: Modulus ranges as reported in the reviewed literature.

4.3 Manipulation Architectures

The stiffness control can be implemented in a real case of the gripper design. After reviewing the soft robotic grippers, a classification of soft robotic gripping solutions was drawn, based upon the principle of gripping, three groups were identified: actuation, controlled stiffness and controlled adhesion [19]. Jamming and low-melting-point materials are used in a controlled stiffness class to allow a gripper to form the shape of an object and then stiffen to support a load without losing the

ability to form. The formalization of actuation economy is formalised by underactuated hands, which are the synergy mapping of Equation (4), and representative architectures are compared in Table 4. The two approaches complement to each other with regards to the problem of rigidity switching and the reduction of the number of actuators.

$$q = Sz \tag{4}$$

Table 4. Comparison of Representative Manipulation Architectures

Architecture	Stiffness strategy	Actuation economy	Application	Ref.
Pisa/IIT SoftHand	Adaptive soft synergies with compliant joints	19 joints driven by 1 actuator (19:1)	Dexterous grasping	5
Universal jamming gripper	Granular jamming of a membrane	Passive conformation, pressure-triggered hardening	Grasping of arbitrary objects	4
Positive-pressure gripper	Jamming with positive pressure	Pressure-driven holding	Enhanced holding performance	2
STIFF-FLOP manipulator	Fluidic actuation with stiffening	Modular soft segments	Minimally invasive surgery	6
Open articulated platform	Variable-stiffness joint modules	Modular rapid prototyping	Research on natural motion	7

Source: Synthesized from the cited sources; the joint-to-actuator ratio is computed from the reported 19 joints and 1 actuator.

4.4 Biological Principles and Dissemination

Biological inspiration is still the major source of design principles. Soft continuum motion is exemplified by the arms of the octopus and worm-like bodies: biological analyses presented in the field show the principles of hydrostatic skeletons and how they may be applied to soft manipulators [20]. This interdisciplinary character is also evident in the distribution of the sources in the corpus - 5 sources (20.8%) are from one of the robotics publications and 4 sources (16.7%) are from one of the journals from the Science-family and Nature. The multi-disciplinary character of venues suggests that transfer between the fields of robotics and materials and biology will be needed for the improvements, as required by the integrated approach outlined in this paper.

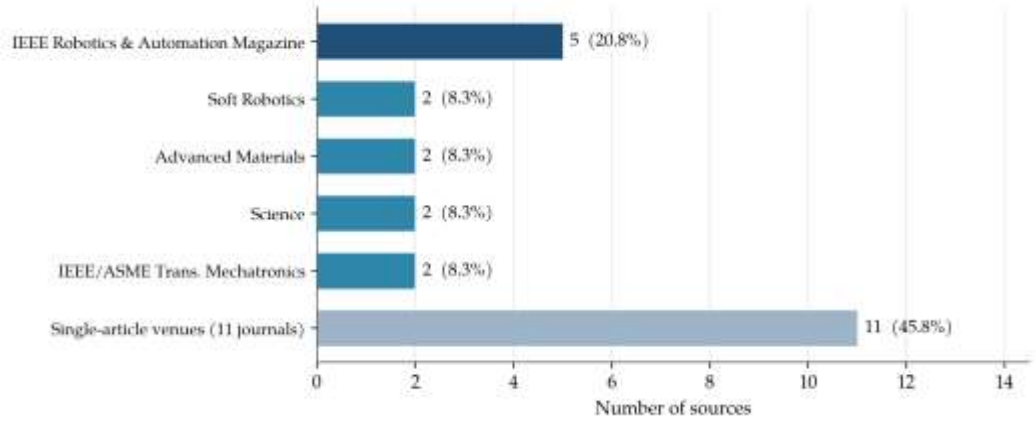

Figure 4. Distribution of Sources Across Publication Venues

Source: Derived from the venues of the supplied corpus.

4.5 Actuator Architectures and Energetics

Compliant actuators were categorized according to the method of introducing and controlling the elasticity, at one end of the spectrum being series-elastic and at the other end being the designs with adjustable stiffness, which were achieved using the antagonistic or mechanically-controlled schemes [21]. There is a constant compliance, provided by the series elastic element, which is defined by Equation (5); adjustable designs can prescribe stiffness as a function of the task requirement. The features of these architectures are briefly summarized in Table 5 and shown in Figure 5. From these two tables and figures, it is clear that there is no one "best" architecture on all the criteria, so you will have to decide which of these you want to be more important for you and choose an architecture that fits your aim based on range, speed, efficiency, compactness, or scalability.

$$\frac{1}{K_{\text{eq}}} = \frac{1}{K_s} + \frac{1}{K_c} \tag{5}$$

Table 5. Comparison of Compliant and Variable-Stiffness Actuation Principles

Architecture	Operating principle	Stiffness behavior	Energy characteristic	Refs.
Series elastic actuator	Fixed elastic element between motor and load	Constant compliance	Stores and releases elastic energy; stiffness not adjustable	21
Antagonistic variable stiffness	Two nonlinear elastic elements acting against each other	Stiffness set by co-activation	Holding stiffness continuously draws power	22, 24
Mechanically controlled (AwAS type)	Lever mechanism changes the effective spring ratio	Continuous adjustment by a small motor	Designed for low-energy stiffness adjustment	11
Granular and layer jamming	Pressure-induced fluid-to-solid transition	Large change, moderate speed	Energy needed mainly to maintain pressure difference	2, 4, 8
Phase-change materials	Thermally induced rigidity transition	Large change, slow transition	Heating and cooling dominate energy cost	15, 23

Source: Qualitative synthesis of the cited sources; ratings corresponding to these entries are plotted in Figure 5.

	Stiffness range	Response speed	Energy efficiency	Compactness	Small-scale feasibility
Series elastic	Low	High	Moderate	High	Moderate
Mechanical VSA	High	Moderate	High	Low	Low
Antagonistic VSA	Moderate	High	Low	Low	Low
Jamming	High	Moderate	Moderate	Moderate	High
Phase-change materials	High	Low	Low	High	High

Figure 5. Qualitative Comparison of Stiffness-Modulation Mechanisms

Source: Ordinal ratings assigned by synthesis of qualitative statements in the cited sources.

In addition to variable impedance actuators, which were reviewed, there are a number of designs that introduce variable stiffness and damping characteristics and also variable equilibrium position, where mechanical complexity, weight of the system and the number of motors required to obtain independent control was found to be the main challenges [22]. According to Equation (6), deflection and stiffness are both important parameters for determining recoverable energy, which is important for dynamic tasks. Both variables have effects, which are illustrated in Fig. 6. As the deflection is fixed at 0.20 rad and the energy stored increases from 2 J to 10 J when stiffness increases from 100 to 500 N·m/rad, the amount of stored energy is proportional to the stiffness. The behavior is clearly such that the stiffness of the compliant element only contributes to stiffness when it is less than 100 N·m/rad, regardless of the stiffness of the actuator, as seen on the right hand side of the figure.

$$E = \frac{1}{2} K \Delta q^2 \tag{6}$$

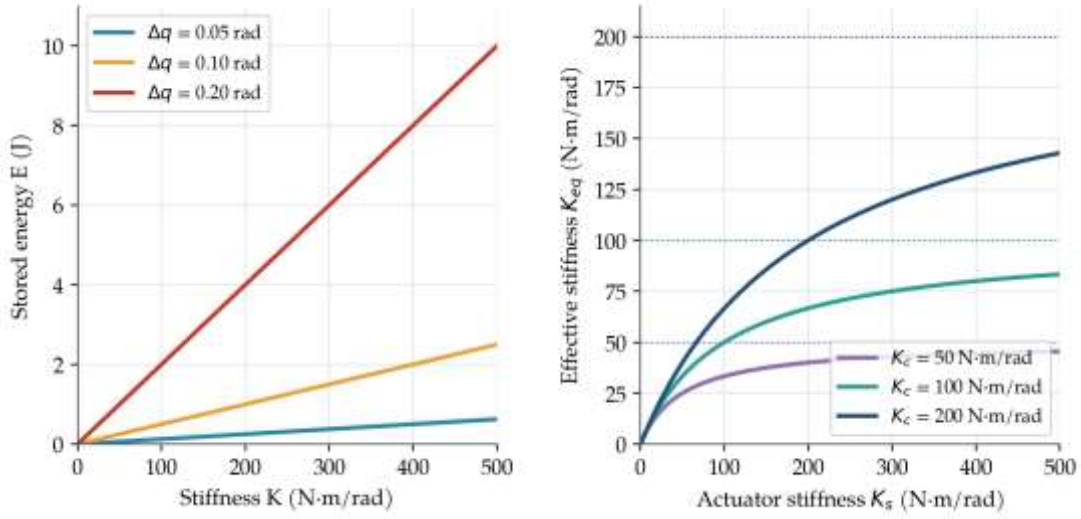

Figure 6. Stored Elastic Energy and Effective Series Stiffness for Illustrative Parameters

Source: Computed from Equations (5) and (6) with illustrative parameter values.

4.6 Material Tuning and Design Outlook

A material (level) rigidity tuning method can be adopted instead of bulky actuators. A survey of controllable and reversible change of rigidity for robotics was carried out including some of the phase transition materials: low melting point alloys and polymers, jamming, and electrically and magnetically responsive materials and some trade-off between stiffness change ratio, response time and energy input were mentioned [23]. Efficiency ratio, as shown in Equation (7), is a way of quantifying these trade-offs and can be seen in Figure 5, which indicates that the phase-change approaches have a high efficiency for range and compactness, but are slow. Therefore, hybrid design, combining a high-speed mechanical component with a small material-level mechanical component is a promising approach for energy adaptive manipulators with large stiffness range.

$$\eta = \frac{E_{\text{out}}}{E_{\text{in}}} \tag{7}$$

From the above synthesis, design recommendations are made, and summarized in Table 6. Design process for variable stiffness actuators, which matches the stiffness and energy requirement of the tasks, was addressed [24] and elastic elements and mechanisms to adjust stiffness and control components were discussed. Surgical applications, where bounded stiffness and limited impact loading are safety-critical, and physical interaction with a robot, further highlight the priorities mentioned in Table 6, while introducing ethical and regulatory issues. The priorities found as a result of this process are modularity, intrinsic energy efficiency, hybridisation of actuation and material and embedding of sensing, all of which have a consistent research agenda.

Table 6. Design Challenges, Evidence, and Optimization Routes

Challenge	Evidence in the corpus	Optimization route	Refs.
Mechanical complexity and weight	Multiple motors and elastic elements required for independent control	Modular open platforms and simplified lever-based designs	7, 22
Energy for holding stiffness	Continuous power needed to maintain rigid states	Intrinsically efficient mechanisms with low-energy adjustment	11, 24
Response time of phase-change tuning	Thermal transitions limit speed	Hybridization with jamming or fluidic elements	15, 23
Safety–performance trade-off	Stiffness must vary with velocity and contact	Stiffness scheduling during task execution	1, 3
Miniaturization	Surface effects dominate at small scale	Material-level stiffness tuning and jamming variants	8, 9
Embedded intelligence	Sensing, actuation, and computation remain separate	Multifunctional materials and integrated energy sources	13, 16

Source: Consolidated from the cited sources.

CONCLUSION

A library of 24 sources of variable-stiffness compliant mechanisms inspired by biology was compiled into four domains and stiffness is best regarded as a schedulable energetic resource, as

demonstrated by analysis. Actuator level mechanisms provide rapid and wide stiffness control at the expense of increased complexity and weight, whereas the jamming approach and materials with phase changes are compact and scalable, but can only provide stiffness control at a slower time scale. Design space for energy adaptive manipulators is needed to span the eight decade difference in modulus between soft and rigid structures and the 19 joint, one actuator efficiency of the synergy-based hands.

Three directions for future research are proposed: compact stiffness control via material level stiffness control coupled with high speed mechanical stiffness control, standardized open platforms for quantitative comparison of stiffness and energy metrics, and embedded sensing and computation to provide stiffness control in stiffening materials independent of task and energy state.

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