Proceedings of the 4th International Conference on Machine Learning and Automation
DOI: 10.54254/2755-2721/2026.37587

Compliant Structure Design for Improved Robot Motion Control Performance

Muhan Yu

School of Engineering, University of Warwick, Coventry, UK
Muhan.Yu@warwick.ac.uk

Abstract. This narrative review examines how compliant structural design redistributes motion control functions between mechanical bodies and computational controllers. It synthesizes theoretical, experimental, and co-design studies on passive dynamic walking, elastic coupling, self-stabilizing locomotion, soft robots, underactuated grasping, morphological computation, and morphology-control optimization. Across these systems, compliance can store and return energy, couple joint motion, shape attracting dynamics, adapt contact geometry, and transform inputs before feedback intervenes. These mechanisms can reduce the number of independently controlled variables and the demands on sensing, modeling, and feedback. Their benefits remain conditional: excessive or poorly located compliance can reduce positioning bandwidth, force capability, repeatability, and robustness outside the intended operating range. The reviewed evidence, therefore, supports allocating compliance to specific functions rather than minimizing stiffness globally. Mechanical self-regulation should be combined with sufficient sensing and actuation for disturbances beyond the passive region, while morphology and control should be optimized jointly with manufacturability, parameter variation, and transfer from simulation to hardware taken into account.

Keywords: Morphological computation, embodied intelligence, soft robotics

1. Introduction

Robot motion control is usually formulated as a problem of designing models, state estimators, and feedback laws. However, every controller must act through a specific physical body, whose mass distribution, geometry, stiffness, and transmission mechanisms jointly determine how actuator commands are converted into motion and contact forces. Research on embodied intelligence therefore treats the mechanical structure as part of the control system rather than as a neutral plant [1]. High-stiffness mechanisms still offer clear advantages when geometric accuracy and disturbance rejection are the dominant requirements. In tasks involving extensive contact or environmental uncertainty, however, their limited passive compliance often increases the demands on sensing, modeling, and feedback. The value of compliant structure design thus lies not only in protecting hardware but also in its potential to redistribute motion control functions between the mechanical body and the computational controller.

© 2026 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

DOI: 10.54254/2755-2721/2026.37587

In this paper, compliant structure design refers to the deliberate introduction and configuration of reconfigurable structures through elastic joints, flexible links, tendon-like transmissions, or soft materials [2, 3]. Compliance describes the relationship between load and deformation; elasticity emphasizes recoverable deformation and the storage and release of mechanical energy; softness usually refers to the distributed deformation produced by a body with a low elastic modulus. Underactuation is a concept on a different dimension: it describes the actuation topology, in which the number of independent control inputs is smaller than the number of mechanical degrees of freedom. Neither concept implies the other: a mechanism can be compliant but fully actuated, or rigid but underactuated. When the two are deliberately combined, compliance can establish mechanical coupling between actuated and unactuated coordinates, allowing contact forces, structural geometry, and stored elastic energy to jointly organize motion that is not controlled by independent commands. This coupling may reduce the number of variables requiring direct control, but it also makes system behavior more dependent on task conditions and mechanical parameters.

This perspective is closely related to morphological computation, although the term does not necessarily mean that a machine performs digital computation in the strict sense. More commonly, its dynamics filter sensory signals, constrain feasible motions, or produce task-related responses before feedback intervenes [4]. Classic locomotion studies illustrate this contribution of the body at different levels. Passive dynamic walking shows that an appropriate configuration of mass and joint mechanics can sustain a gravity-driven gait with very little active input [5]. Passive gait generation and elastic coordination address different control problems, but both can improve specific performance measures only when morphology, environment, and task are matched.

Similar mechanisms are also present in manipulation tasks and soft robots. Lower stiffness may reduce positioning bandwidth, distributed deformation increases the difficulty of state estimation and modeling, and material hysteresis and contact-dependent coupling may also impair repeatability. The key design question should therefore be considered in context.

Joint optimization of morphology and control can identify structures whose physical dynamics are more conducive to task completion than a controller operating on a fixed body, and scalable co-optimization of morphology and control in embodied machines has demonstrated this potential [6]. Learning compact representations of soft-body dynamics for specific tasks also allows material and control parameters to be adjusted simultaneously within a unified optimization loop [7]. The main influence of this work is not confined to computational methods; it also changes the approach to design: system performance arises from the allocation of functions between the structure and the controller, rather than from fixing the body in advance and then tuning the controller separately. Both studies, however, rely primarily on simulation, so manufacturability, model discrepancies, hardware differences, and transfer to real environments remain important factors limiting their performance gains.

Existing reviews have established broad foundations for soft robotics and morphological computation, respectively, but the effects of compliant design on control are still often treated as disconnected cases or described broadly as a positive attribute. By synthesizing representative theoretical, experimental, and co-design studies, this paper examines how specific structural choices produce physical mechanisms, how these mechanisms affect motion control outcomes, and under what boundary conditions these mechanisms remain effective. The paper first compares evidence from passive walking, elastic coupling, self-stabilizing locomotion, soft robots, and underactuated grasping. It then discusses the matching of structural parameters to task requirements, and finally evaluates joint optimization of morphology and control and the associated challenges of transfer to hardware. Organizing the literature along the chain of structural choices, physical mechanisms,

DOI: 10.54254/2755-2721/2026.37587

control outcomes, and limits of applicability can provide a basis for causal comparison across different types of systems. The significance of this paper lies in distinguishing evidence-supported, task-specific advantages from broad claims about compliance, and in deriving clearer design principles for integrating mechanical structures and control methods in reliable robotic systems.

2. Compliant structures and motion control

Compliance currently changes motion control through two main pathways. Local elastic elements regulate energy exchange and stability around specific coordinates, whereas distributed soft or underactuated structures use contact and deformation to organize multiple coordinates jointly. In either case, the key issue is not whether a mechanism is compliant, but which control function its mechanical structure performs and over what operating range that function is effective. The first pathway mainly concerns gait generation, energy exchange, and recovery from disturbances in locomotion systems; the second mainly concerns shape adaptation, contact organization, and information processing in soft bodies and underactuated mechanisms.

2.1. Elasticity and passive motion regulation

Passive dynamic walking provides the clearest limiting case. McGeer demonstrated that a mechanism with appropriate proportions can convert gravity and alternating leg motion into a repetitive gait without relying on trajectory tracking. Collins et al. retained this passive organization of dynamics while using a small amount of actuation to compensate for energy losses during walking on level ground. Their three robots required less control effort and consumed less energy than conventional powered bipedal robots of the time [8]. The distinction between the two studies is that McGeer treated gravity and structural parameters as the main sources of gait generation, whereas Collins added a small amount of actuation to this foundation to compensate for energy losses during walking on level ground. The former shows that mechanical dynamics can organize gait, while the latter further demonstrates that active control can focus on energy compensation without specifying all joint motions. Together, the two studies show that low control effort does not mean eliminating actuation altogether; instead, the mechanical structure first constrains feasible motion, and the controller then maintains the required energy. This advantage still depends on the robot operating near the range for which its mechanical gait was designed, and therefore cannot be directly extrapolated to conditions involving substantial changes in speed, slope, or load.

Elastic coupling can extend this principle by transferring energy and coordinating motion across joints. In the bipedal robot studied by Iida, Rummel, and Seyfarth, passive knee and ankle joints were connected by four extension springs that mimicked biarticular muscles [9]. With suitable spring parameters, simple periodic hip inputs could support walking and running without global sensory feedback. These springs do more than reduce impacts: their moment arms and timing couple joint motions, alter touchdown dynamics, and release stored energy at stages appropriate to the task. The key variables are not compliance itself, but the location, routing, and timing of elastic coupling.

Passive regulation is better suited to serving as a foundation beneath a supervisory layer and need not completely replace active control. Iida and Pfeifer drove a quadruped robot with simple sinusoidal position commands and regulated speed mainly through phase adjustments, while interactions between the body and the ground absorbed small disturbances, enabling self-stabilizing bounding [10]. Ringrose also demonstrated sensorless self-stabilizing running in a model and a physical single-legged robot, but explicitly limited the conclusions to specific terrain and operating conditions [11]. These systems exhibit the same causal chain: elastic or inertial dynamics form

DOI: 10.54254/2755-2721/2026.37587

attracting motion patterns, and feedback only needs to manage energy, phase, or state transitions. Once terrain, load, or speed falls outside this region of attraction, additional sensing and corrective capabilities are required.

Taken together, these locomotion studies suggest that a more reasonable approach is to adopt hierarchical control. Mechanical design can provide rapid local responses without waiting for sensing and computation, and elastic energy storage can also reduce repeated work by actuators. Such passive responses are helpful, however, only when their direction and timescale match the disturbances and the task. Excessive compliance can reduce foot placement accuracy, introduce oscillations, or delay force transmission; insufficient damping may preserve both useful and unwanted motions. In practical design, the nominal gait and expected disturbances should be defined first, followed by the selection of stiffness, damping, and geometry to establish a region around the nominal gait from which recovery is possible, while retaining feedback to handle variations that mechanical dynamics cannot suppress.

2.2. Simplifying motion control through soft and underactuated structures

Distributed compliance shifts the mechanism from energy regulation at a few joints to shape adaptation across the entire body or contact surface. Simplifying the command space therefore does not mean that design or prediction becomes equally simple. Rus and Tolley noted that soft materials can deform continuously and conform to uncertain environments, but the large number of effective degrees of freedom also makes conventional rigid-body models difficult to apply [2]. The pneumatic quadruped robot with five actuators designed by Shepherd et al. illustrates both aspects: different combinations of air channels produced crawling and undulating gaits without conventional joints or sensors, and the nonlinear elastomeric structure converted simple valve-control sequences into complex motion [12]. However, the platform was susceptible to puncture, had limited pressure and load capacity, and relied mainly on empirical modeling of its nonlinear response.

In manipulation tasks, passive shape matching can replace part of grasp planning. Brown et al. used a bag of granular material that could flow around and envelop an object before jamming and rapidly stiffening when evacuated [13]. A single change in pressure state could generate holding forces through friction, suction, and geometric interlocking, eliminating the need to control multiple fingers independently or estimate all contact points. The mechanism nevertheless remains subject to constraints: flat objects that cannot be sufficiently enveloped cannot be lifted, airtightness affects suction forces, and excessively fine particles slow the evacuation process. The importance of this case is that it places some of the "intelligence" in a reversible material transition, while clearly showing that object geometry and interface conditions determine whether this simplification of control is possible.

The RBO Hand demonstrates another approach. Underactuation and compliance distribute a small number of control commands across multiple contact points. With only four actuated degrees of freedom, the hand achieved 31 of the 33 postures in a standard taxonomy of human grasps, and its measured grasp posture space had a higher dimensionality than its actuation space [3]. Contact with objects provided additional variation, and the hand deformed until contact forces and geometric relationships jointly selected a feasible posture. This mechanism achieved robust and diverse grasps with relatively simple commands, but its low grasp stiffness limited tasks requiring large forces to be exerted on the environment, while the pneumatic hardware and nonlinear deformation also increased the difficulty of precise planning. Compliance effectively trades precise posture control for adaptability, and whether this trade is beneficial depends on the force, accuracy, and repeatability required by the task.

DOI: 10.54254/2755-2721/2026.37587

These studies of soft robots further specify the sense in which the body can process information. Hauser et al. showed theoretically that sufficiently rich mass-spring dynamics can provide nonlinear transformations and fading memory to a simple readout layer [14]. Nakajima et al. further used the measured dynamics of a silicone arm in water to emulate nonlinear dynamical systems, while noting that performance depended on actuation conditions, sensing, material responses, and environmental damping [15]. These findings support treating body dynamics as a computational resource, but do not imply that the body can independently serve as a controller. As Müller and Hoffmann emphasized, useful contributions must be identified relative to a specific task and alternative control architectures [4]. Softness reduces explicit control commands only when the physical dynamics of the soft body can reliably transform inputs into the required motion.

3. Matching and co-optimization of structure and control

Treating structural compliance as a design variable rather than a universal goal shifts the focus to how mechanical responses match task requirements and how these responses can be jointly optimized with sensing and control. Evaluation must also distinguish nominal performance from recovery after disturbances. This section first discusses the selection of structural parameters and then analyzes how the joint design of structures and control can identify combinations that conventional sequential processes may overlook.

3.1. Structural parameters matched to the task

Robot stiffness should not be reduced uniformly across all parts, but should be set separately according to the function and task requirements of each part. There are two main approaches to achieving compliance. One is to introduce elastic elements into joints or transmission mechanisms, giving the robot intrinsic compliance that does not depend on the controller and thereby allowing it to store and release energy, cushion collisions, and limit impact torques, while continuing to provide mechanical protection even during power loss or control failure. The other is to retain relatively high stiffness in the transmission itself and use torque sensing and feedback control to dynamically adjust the robot's response to external forces, allowing it to exhibit adjustable compliance while maintaining high stiffness during precise positioning.

Stiffness should be selected according to function and location rather than minimized globally. Intrinsic joint elasticity can store energy, limit impact torques, and continue to protect control failure. Active torque control can dynamically adjust the robot's response to external forces through torque sensing and feedback control without permanently sacrificing rigidity, allowing it to exhibit adjustable compliance while maintaining high stiffness during precise positioning. The work of Albu-Schäffer et al. shows that neither approach has an absolute advantage [16]. Variable-stiffness actuation improves impact resistance and energy storage capacity, but also increases the number of actuators and the difficulty of control, reduces mechanical bandwidth and absolute positioning accuracy, and limits the forms of Cartesian compliance that can be achieved. For periodic locomotion, elasticity near the main energy-exchange coordinates may be beneficial; for precise positioning, local or adjustable compliance is usually preferable to a transmission system that is softened throughout.

Suitable parameter combinations also depend on timescales and system states. Related studies of hopping models reached similar conclusions: nonlinear muscle models and motor-driven models exhibited different degrees of morphological computation, and this contribution varied between the stance and flight phases [17]. Average measures of efficiency or control complexity may therefore

DOI: 10.54254/2755-2721/2026.37587

conceal when the body actually contributes. Stiffness, damping, sensor locations, and actuation methods should be evaluated separately across different stages of behavior and under disturbances relevant to the application.

A sound matching process should follow the causal chain adopted in this paper. Designers should first define objectives such as recovery margin, energy consumption per unit distance, grasp success rate, or tracking error, and identify the physical mechanism expected to improve the selected objective. Mechanical parameters should then be varied with controller resources and test conditions explicitly specified. Comparisons should include a rigid baseline or baselines with different compliance configurations, rather than merely presenting the best compliant prototype. Losses in bandwidth, accuracy, load capacity, and robustness outside nominal conditions should also be reported. Locomotion tests should not be confined to a single limit cycle, but should cover different speeds, slopes, and disturbances; manipulation tests should vary object geometry, friction conditions, and approach errors. Parameter sensitivity should also be reported, because an excessively narrow optimal range may be difficult to manufacture or maintain over time. This approach can prevent gains from a more capable controller from being misattributed to passive adaptation, and reveal whether structural advantages persist when material properties, contact, or load changes.

3.2. Joint optimization of structure and control

The long-term motivation for co-optimization is that the body and the controller jointly determine each other's effective search spaces. Sims's virtual creatures provided an early demonstration: genetic algorithms simultaneously generated three-dimensional morphologies and neural control systems, producing swimming, walking, jumping, and following behaviors that would be difficult to specify manually one by one [18]. The study demonstrated the feasibility of joint search, but its experiments took place only in simplified virtual environments and did not include manufacturing constraints. Cheney et al. subsequently identified a specific obstacle in such searches: most morphological mutations initially impair controllers that have already adapted to the old body, making the search prone to stagnation [6]. Their "morphological innovation protection" method temporarily reduced selection pressure after a change in the body, giving the controller time to readapt and improving convergence across different initial conditions. This development shows that successful co-design requires not only a common objective but also adaptation of morphology and control on mutually compatible timescales.

Learning-based methods advance the question from whether morphology and control can be optimized jointly to which physical properties make the body easier to control or learn to control. In more difficult simulation tasks, dynamics-oriented features led to more reliable convergence than baselines based on geometric clustering, but the cost of three-dimensional optimization remained high, and retraining the representation model sometimes disrupted previous progress. Gupta et al. used deep evolutionary reinforcement learning to evaluate different morphologies on new locomotion and manipulation tasks [19]. Across three evolutionary environments, greater environmental complexity led the system to select morphologies that learned new tasks more quickly and had greater passive stability and energy efficiency. Gupta et al. linked morphology to learning speed and transfer across tasks. Both studies remain primarily simulation-based, so their benefits depend on the accuracy of body, contact, and sensing models.

Hardware validation changes the optimization objective once again. Howison et al. described reality-assisted evolution as an alternating closed loop: data-driven simulations propose soft robot designs, batches of physical prototypes test them, and the resulting measurements are then used to

DOI: 10.54254/2755-2721/2026.37587

update the model and estimates of transferability [20]. This loop can expose manufacturing constraints and model discrepancies before the search concentrates on unrealizable designs. Its applicability is nevertheless bounded by experimental capability: physical experiments are expensive and noisy, and soft materials also present aging, batch variation, and sensing difficulties. Repeated experiments must distinguish design effects from manufacturing variability, rather than merely rank one-off prototypes. Credible co-design should not only optimize nominal task performance but also take into account manufacturability, parameter tolerances, sensing feasibility, and recovery under uncertain conditions. Overall, the research objective has shifted from finding the best morphology in simulation to finding combinations of bodies and controllers that retain an effective division of functions after learning, manufacturing, and transfer.

4. Conclusion

This paper has examined how compliant structures improve motion control along the chain of "structural choices, physical mechanisms, control outcomes, and limits of applicability." The evidence supports conditional rather than universal conclusions: elastic elements can form attracting motion patterns, store and release energy, and coordinate joints; distributed soft bodies can conform to uncertain environments; and underactuation can distribute a limited set of commands across multiple contact points. When geometry, stiffness, damping, and material responses match the task, these mechanisms can reduce the burden on feedback. Passive walkers, spring-coupled legs, soft robots with multiple gaits, granular grippers, and compliant hands demonstrate different allocations of functions between mechanical and computational control.

These studies also define the limitations. Compliance may reduce positioning bandwidth and force capability, amplify oscillations or hysteresis, increase the difficulty of state estimation, and make systems more sensitive to differences in terrain, load, contact, pressure, and materials. A smaller command space does not mean that the overall system is simpler: control complexity may be transferred to structure, manufacturing, calibration, or task constraints. Claims of morphological computation are adequately supported only when the transformations or regulation provided by the body are explicitly identified, compared with credible alternatives, and reported together with their range of reliability.

Three principles follow. First, compliance should be allocated according to explicit functions and evaluated using task measures, rather than treated as a universal sign of adaptability. Second, mechanical self-regulation needs to be supported by sufficient sensing and actuation to handle state transitions and disturbances outside the passive region. Third, morphology, observation, and control should be optimized jointly, while manufacturability, parameter tolerances, and transfer to hardware are also examined. Future research should compare the allocation of functions between structure and control using common benchmarks, quantify differences in the body's contribution across stages and states, and close the loop between simulation and repeated physical experiments. Compliant design thus allocates part of control to machine dynamics. It does not eliminate control, but determines where control is implemented.

References

[1] Pfeifer, R., Lungarella, M., & Iida, F. (2007). Self-organization, embodiment, and biologically inspired robotics. *Science, 318*(5853), 1088–1093.
[2] Rus, D., & Tolley, M. T. (2015). Design, fabrication and control of soft robots. *Nature, 521*(7553), 467–475.
[3] Deimel, R., & Brock, O. (2016). A novel type of compliant and underactuated robotic hand for dexterous grasping. *The International Journal of Robotics Research, 35*(1–3), 161–185.

DOI: 10.54254/2755-2721/2026.37587

[4] Müller, V. C., & Hoffmann, M. (2017). What is morphological computation? On how the body contributes to cognition and control. *Artificial Life, 23*(1), 1–24.
[5] McGeer, T. (1990). Passive dynamic walking. *The International Journal of Robotics Research, 9*(2), 62–82.
[6] Cheney, N., Bongard, J., SunSpiral, V., & Lipson, H. (2018). Scalable co-optimization of morphology and control in embodied machines. *Journal of the Royal Society Interface, 15*(143), Article 20170937. https://doi.org/10.1098/rsif.2017.0937
[7] Spielberg, A., Zhao, A., Hu, Y., Du, T., Matusik, W., & Rus, D. (2019). Learning-in-the-loop optimization: End-to-end control and co-design of soft robots through learned deep latent representations. In *Advances in Neural Information Processing Systems 32*.
[8] Collins, S., Ruina, A., Tedrake, R., & Wisse, M. (2005). Efficient bipedal robots based on passive-dynamic walkers. *Science, 307*(5712), 1082-1085.
[9] Iida, F., Rummel, J., & Seyfarth, A. (2008). Bipedal walking and running with spring-like biarticular muscles. *Journal of Biomechanics, 41*(3), 656-667.
[10] Iida, F., & Pfeifer, R. (2004). 'Cheap' rapid locomotion of a quadruped robot: Self-stabilization of bounding gait. In *Proc. 8th Int. Conf. Intelligent Autonomous Systems (IAS-8)*, 642-649.
[11] Ringrose, R. (1997). Self-stabilizing running. In *Proc. IEEE Int. Conf. Robotics and Automation (ICRA)*, 487-493.
[12] Shepherd, R. F. et al. (2011). Multigait soft robot. *Proceedings of the National Academy of Sciences of the United States of America, 108*(51), 20400-20403.
[13] Brown, E., Rodenberg, N., Amend, J., Mozeika, A., Steltz, E., Zakin, M. R., Lipson, H., & Jaeger, H. M. (2010). Universal robotic gripper based on the jamming of granular material. *Proceedings of the National Academy of Sciences of the United States of America, 107*(44), 18809-18814.
[14] Hauser, H., Ijspeert, A. J., Füchslin, R. M., Pfeifer, R., & Maass, W. (2012). Towards a theoretical foundation for morphological computation with compliant bodies. *Biological Cybernetics, 105*(5-6), 355-370.
[15] Nakajima, K., Hauser, H., Li, T., & Pfeifer, R. (2015). Information processing via physical soft body. *Scientific Reports, 5*, Article 10487.
[16] Albu-Schäffer, A., Eiberger, O., Grebenstein, M., Haddadin, S., Ott, C., Wimböck, T., Wolf, S., & Hirzinger, G. (2008). Soft robotics: From torque feedback-controlled lightweight robots to intrinsically compliant systems. *IEEE Robotics & Automation Magazine, 15*(3), 20–30.
[17] Ghazi-Zahedi, K., Haeufle, D. F. B., Montúfar, G., Schmitt, S., & Ay, N. (2016). Evaluating morphological computation in muscle and DC-motor driven models of hopping movements. *Frontiers in Robotics and AI, 3*, Article 42.
[18] Sims, K. (1994). Evolving virtual creatures. In *Proc. SIGGRAPH '94*, 15–22.
[19] Gupta, A., Savarese, S., Ganguli, S., & Fei-Fei, L. (2021). Embodied intelligence via learning and evolution. *Nature Communications, 12*, Article 5721.
[20] Howison, T., Hauser, S., Hughes, J., & Iida, F. (2020). Reality-assisted evolution of soft robots through large-scale physical experimentation: A review. *Artificial Life, 26*(4), 484–506.