A Review of Variable Stiffness Actuator (VSA) for Legged Robots.

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***Abstract* – This paper reviews the progression of legged robot design from traditional rigid, torque-driven legs to systems that actively regulate mechanical compliance using Variable Stiffness Actuators (VSAs). Conventional prismatic, articulated, and redundant leg architectures can produce high force and complex motion, but they suffer from high impact loads, poor energy recovery, heavy distal mass, and increased control burden in unpredictable terrain. VSAs address these limitations by allowing real-time tuning of joint stiffness to switch between compliant, shock-absorbing behavior and stiff, load supporting behavior as tasks and ground conditions change.**

This work presents the main VSA design strategies such as antagonistic actuation, active spring pretension, geared elastic transmission, proximally located cable-driven actuation, and magnetorheological stiffness control and examines how each approach trades off complexity, bandwidth, energy cost, and integration. It then studies representative implementations: tensegrity-based joints with centralized stiffness regulation; cable–pulley and crank–slider designs with remotely actuated preload; muscle-like compliant actuators with controllable near-zero stiffness; permanent-magnet antagonistic joints capable of independently modulating both angle and stiffness; high-torque series elastic systems that decouple position from stiffness; compact leaf-spring/ball-screw modules with fast sliding preload adjustment; and quasi-passive assist legs that mechanically reconfigure stored elastic energy to deliver high lifting support.

Taken together, these systems show that VSAs enable lightweight integration at the limb, large and rapid stiffness variation from highly compliant to near-rigid, low holding power, safer physical interaction, improved impact tolerance, and partial energy recovery. The overall conclusion is that variable stiffness is becoming a core requirement for next-generation legged robots, driving higher efficiency, robustness, and safety in complex, real-world environments.

***Keywords*- Variable Stiffness Actuators (VSA), legged robots, principles of VSA design.**

I. Introduction

Legged robots are robotic systems that use multiple articulated legs for locomotion, mimicking biological animals to achieve mobility across complex and uneven terrains [1], [2]. Their key advantage lies in their capability to negotiate obstacles, climb slopes, and maintain stability where wheeled or tracked robots face limitations [1], [2]. However, most conventional legged robots rely on rigid actuation systems with fixed mechanical stiffness, which introduces several drawbacks [1], [2], [3]. Conventional rigid-jointed robots face several significant design challenges. They typically exhibit poor shock absorption and consume high amounts of energy because their motors must constantly work to maintain position without inherent mechanical compliance. This rigidity also limits their adaptability to different surface conditions and increases the risk of structural damage from unexpected impacts or collisions [1], [4], [5], [6], [7]. Furthermore, since these robots lack mechanical compliance, their control algorithms must become overly complex. This complexity is needed to compensate for the joint rigidity under heavy loads and multi-contact scenarios, ultimately limiting their real-time adaptability and overall efficiency in unpredictable environments [1], [2], [3]. Variable Stiffness Actuators (VSAs) address these challenges by providing adjustable mechanical compliance in robotic joints [3].Unlike fixed-stiffness actuation, VSAs enable robots to dynamically tune the stiffness of their limbs during locomotion, depending on task requirements and environmental conditions [2], [3], [7]. This capability allows legged robots to absorb impacts more effectively, store and release elastic energy for efficient movement, and maintain stable ground contact on varied terrains. By mimicking muscle behaviour, VSAs reduce the burden on control systems by incorporating passive adaptability, thereby enhancing overall performance and safety [3], [7]. The active modulation of stiffness in VSAs improves energy efficiency, durability, and interaction robustness, making them indispensable for advancing the agility and resilience of legged robots in real-world applications [2], [3].

Variable Stiffness Actuators generally combine compliant elements, such as springs, with motor-driven mechanisms to modulate output stiffness. The mechanisms underlying VSAs vary widely, including antagonistic arrangements of two motors applying forces on springs, adjustable spring preload systems, cable-driven compliant structures, and semi-active materials like magnetorheological fluids whose viscosity changes with magnetic fields to modulate stiffness [2], [3]. These architectures not only allow stiffness tuning over a broad range but also enable energy storage and release similar to biological muscles [2], [3]. For legged robots, cable-driven VSAs facilitate lightweight distal limbs by locating heavy actuation proximally and transmitting force through cables, increasing efficiency and agility [1], [7]. Meanwhile, tensegrity-based designs leverage networks of flexible cables and rigid elements to achieve structural compliance and stiffness modulation in a compact form [3] Ongoing research focuses on improving the speed, accuracy, and repeatability of stiffness modulation while maintaining mechanical robustness suited for harsh operational conditions encountered by legged robots [2], [3], [7].

II. Conventional Principles of Leg Design

Conventional leg design principles in legged robots focus on mimicking biological limb structures through distinct kinematic and actuation strategies, each with specific advantages and limitations [4], [8], [9] Legged systems are explicitly inspired by animals to traverse uneven, cluttered, and deformable terrain where wheeled and tracked robots struggle, quadruped and single-leg designs are typically grouped into prismatic (telescopic), articulated, and redundant / extended articulated legs; prismatic legs rely on a rotary joint plus a linear prismatic joint, articulated legs use two rotary joints for 2-DOF motion, and redundant articulated legs add an additional rotary joint and supporting springs to improve motion stability and energy-use efficiency [8], [9]. These leg structures are usually realized with rigid-link mechanisms, which are strong and robust but suffer from sealing and durability issues in harsh environments like flooded or sandy terrain, motivating more compliant and adaptive solutions [4], [5], [6], [9]. At the whole-robot level, high-performance quadrupeds combine multiple actuated joints per leg and high-torque power sources (hydraulic, electric, or hybrid) to achieve dynamic behaviors such as stair climbing, high-speed running, heavy-load transport, and agile inspection in unstructured environments[4], [5], [6], [8]. Direct-drive (DD) legged platforms like Minitaur go even further by eliminating gearboxes and directly coupling high-bandwidth motors to the legs, which improves transparency, robustness, and control bandwidth across multiple morphologies with two or more active DOFs per leg, but also creates demanding design trade-offs in actuator sizing and leg linkage design to maintain torque and efficiency [6], [8], [10] .

Prismatic (telescopic) legs are characterized by linear sliding/prismatic actuation that extends and retracts the leg along (approximately) a straight line; mechanically, a telescopic leg typically combines a hip joint with a linear prismatic element so that leg length changes by axial extension and compression rather than multi-axis rotation [8], [9], [11]. Telescopic / prismatic legs often use pneumatic cylinders, hydraulic actuators, or electric drives paired with linear or torsional springs so that vertical jumping and impact absorption come largely from storing and releasing energy in the spring or rod during stance and then re-extending during push-off, enabling repeated hopping and leaping with relatively simple mechanics [8], [11]. Classic single-leg

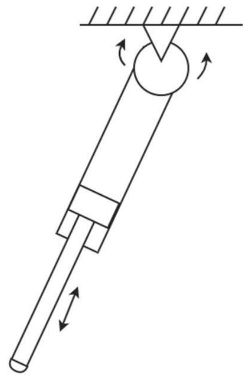

Fig.1. Prismatic Leg

"hopper" designs driven by paired pneumatic cylinders can vertically hop in place, hop forward at varying speeds, and clear small obstacles by regulating hip angle and telescopic spring compression/extension to manage thrust and body pitch, demonstrating that simple telescoping legs can generate agile ballistic motions with high energy return [8], [11]. Because these prismatic legs mostly actuate along one primary axis, they efficiently channel actuator effort into leg length change, making them attractive for high-power jumping with minimal linkage complexity [8], [11] Their biggest limitation is directional versatility: many telescopic (prismatic) legs start as 2D systems with a single hip rotation, so the robot can only jump in the sagittal plane (forward/back) and cannot natively reject lateral disturbances or step sideways, which reduces adaptability on cluttered or sloped terrain [8], [11] To address this, later "3D telescopic" legs introduce extra hip DoFs so the leg can swing laterally and generate omnidirectional hops, improving recovery from lateral impacts and enabling motion forward, backward, left, and right in more realistic field conditions [8], [11]

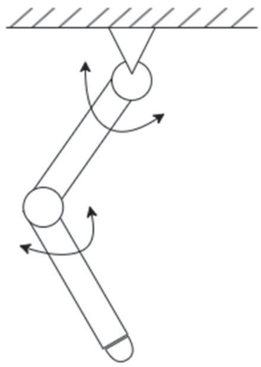

Fig.2. Articulated Leg

Articulated legs are composed of multiple rotary joints analogous to biological hips, knees, and ankles, typically giving each leg two or more rotational degrees of freedom, and redundant articulated legs add a further joint and springs to increase stability and energy efficiency under load [5], [8], [9]. These multi-DOF legs allow coordinated flexion/extension and lateral swing, letting quadrupeds walk, trot, run, climb, and carry heavy payloads over rubble, slopes, stairs, and deformable ground where wheeled systems would tip or get stuck; hydraulically actuated platforms like BigDog/LS3 and HyQ deliver high torque and load capacity for rough outdoor terrain, while electrically actuated robots like ANYmal, SpotMini, Laikago, and MiniCheetah leverage precise torque-controlled joints and direct-drive motors for agile climbing, stair traversal, backflips, and dynamic inspection in human environments [4], [5], [6]. Mechanical linkages such as planar four-link and five-bar mechanisms are frequently used in these articulated legs to shape force transmission and jumping performance: examples include Stanford Doggo's planar four-link jumping leg and the five-bar linkage–based direct-drive legs analyzed for efficient force production and thermal load management in DD robots, which help deliver high agility despite removing gearboxes [5], [8], [10]. The drawbacks are significant: multi-joint articulated legs raise overall kinematic and dynamic complexity, require high-precision real-time coordination across many actuators, and often place heavy actuators or transmissions near the distal joints, which increases leg inertia and control burden during fast swing phases [1], [6], [8], [11]. Even when perception and intelligent control are added to stabilize motion and improve terrain adaptation, this increases system complexity, sensing requirements, and power consumption [4], [5], [10].

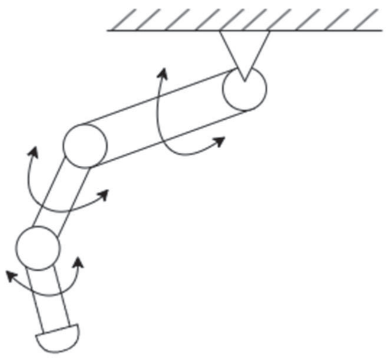

Fig.3. Redundant Articulated Leg

Redundant or extended articulated legs push this idea further by adding extra joints and embedded elastic elements (supporting springs) on top of the basic articulated chain; this redundancy increases the reachable workspace of the foot and improves motion stability and energy-use efficiency under varying load conditions and contact scenarios [5], [8], [9]. Designs that scale leg length or mechanically amplify joint motion (for example, spring-loaded pantograph and scissor-link legs) can generate large end-effector motion ranges and precise foot placement in cluttered environments, but these mechanisms also add structural and control complexity, increase actuator loading, and may increase weight and maintenance difficulty as robots scale up [1], [5], [6], [7], [8]]. Proximal cable-driven actuation in these scalable/"pantograph-like" legs intentionally routes actuation to the body instead of the distal joints, reducing leg mass and inertia and letting springs store/release energy during stance while mechanically decoupling the motor from high shock loads, but this improvement comes at the cost of higher force demands on the remaining actuators and more elaborate transmission design [1], [6], [8].

Each of these conventional leg principles addresses specific locomotion challenges but also shows core drawbacks: prismatic/telescopic legs excel at vertical thrust and impact absorption through spring-loaded axial extension but originally lack lateral agility and disturbance rejection in complex terrain [8], [11]; articulated and redundant articulated legs deliver versatile, terrain-aware gait control but increase distal inertia, actuator stress, and control complexity as DoFs multiply [4], [5], [6], [12]; and direct-drive/high-transparency designs remove gearboxes to gain robustness, controllability, and kHz-scale tunable compliance, but then face severe torque and force-budget constraints that make linkage optimization and actuator sizing very challenging [6], [8], [10]. These limitations motivate the integration of Variable Stiffness Actuators (VSAs), which dynamically adapt joint stiffness and compliance [1], [8], [11]. VSAs and related variable-stiffness elastic actuation concepts actively tune joint stiffness while also controlling equilibrium position, often by antagonistic springs, adjustable preloads, or rack-and-gear compression mechanisms; examples include AMASC, and L-MESTRAN, which modulate stiffness through mechanisms like opposing springs or adjustable spring compression to match stride frequency and hopping demands [8], [11]. Traditional series elastic actuators (SEAs) already improve force control precision and absorb ground impact shocks, but their stiffness is typically fixed at design time, limiting maximum operating speed and load range; in contrast, variable stiffness designs let the robot adapt limb stiffness across tasks like running, jumping, or landing on rough ground, improving disturbance rejection and safe interaction [8], [11]. New tensegrity-based legs go further by combining cable-driven tensegrity joints (flexible tendons + rigid struts) with an actively controlled pre-tensioning mechanism to modulate rotational joint stiffness, achieving omnidirectional compliance, large range of motion (~175°), and shock reduction while maintaining integrated, lightweight actuation suitable for mobile robots [1], [3]. Other variable-stiffness legs exploit semi-active smart materials such as magnetorheological fluids and elastomers, which can change stiffness within milliseconds via magnetic fields; these designs have demonstrated tunable leg stiffness increases of over 250%, reductions in cost of transport, and improved stability over changing ground condition [2], [12]. By embedding compliance and fast stiffness modulation directly into the leg mechanism rather than relying only on high-rate feedback control VSAs offload part of the stabilization and shock-absorption problem to the mechanics, lower the burden on real-time control, and enable safer, more energy-efficient, and more terrain-robust locomotion in agile legged robots operating in the real world [1], [3], [4], [6], [11].

A. Transmission Mechanisms for Legged Robots

1. Direct Drive

Direct drive transmission mounts the actuator generally an electric motor directly to the joint it controls, eliminating intermediate components like gears or cables [5], [10]. This setup allows highly precise and responsive control due to the direct mechanical coupling between the motor and joint, minimizing transmission lag and providing high-fidelity force feedback [10]Advantages include exceptional control accuracy, low friction and backlash, and simplified control dynamics [10], [12]. However, the major drawback is the motor's mass placed distally, increasing the leg's inertia and making rapid, energy-efficient limb swings challenging, which limits agility and speed [4], [5], [10]. In addition, even in systems that try to exploit direct-drive transparency and bandwidth, designers face hard trade-offs in torque production, thermal limits, linkage geometry, and achievable dynamic range, which become more severe as speed and jump performance demands rise [8], [10].

2. Cable or Belt-Driven Transmission

Cable-/belt-driven transmissions route tensile elements over fixed/movable pulleys to convert motor rotation into joint motion with leverage; antagonistic winch paths provide clean rotary output, large travel, and built-in reduction (≈1:12 in tensegrity joints) [3]. By routing through a central shaft and pulley blocks, heavy actuators can be mounted off-joint to cut distal mass and simplify integration [13], [14]. In belt variants, correct pretension is critical non-backdrivable screws/worms hold settings safely; too little causes slip, too much limits travel/overloads the belt defining a reliable operating window [15]. Pulley blocks can also convert rotation to linear spring compression, letting one routed cable drive multiple compliant units within compact actuator modules [13].

3. Series Elastic or Compliant Mechanisms

Series elastic and compliant transmissions employ elastic components, typically springs, between the motor and joint [12], [16]. These elements absorb shocks and sudden loads, protecting mechanical parts and enhancing durability during repeated ground impacts or unexpected collisions [12], [16]. They also store elastic energy during limb compression, which can be reused to improve energy efficiency in cyclic motions such as walking or hopping [12]. Additionally, compliant transmissions smooth force delivery and reduce impact disturbances, enhancing interaction safety for physical robot–environment contact and even human-interactive tasks [2], [16]. The downside includes potential control complications arising from compliance-induced delays, requiring advanced control strategies to manage oscillations and maintain precise joint positioning [12], [16]. Modern Variable Stiffness Series Elastic Actuators (VSSEA) extend this concept by actively modulating stiffness over a very wide range (from very soft to extremely stiff, up to ~1000 Nm/rad and beyond) while maintaining high torque density and fast stiffness adjustment rates, on the order of thousands of Nm/rad/s [16]. In these systems, stiffness and equilibrium position are decoupled using a modular design with two actuators: one actuator regulates joint position/torque, and a second (often direct drive) actuator tunes stiffness by mechanically adjusting compliant elements such as leaf springs [16]. This architecture enables rapid stiffness changes, near-zero energy cost to hold a chosen stiffness at equilibrium, and bounded energy cost even during modulation, which directly improves safety, adaptability, and efficiency under changing load and terrain conditions [12], [16].

TABLE 1. COMPARISON OF TRANSMISSION MECHANISMS

Transmission Type	Advantages	Disadvantages	Typical Applications
Direct Drive	High precision, immediate force feedback, high bandwidth	High distal mass, higher inertia, energy-intensive motion	Simple joints, slow or moderate-speed robots
Cable/Belt-Driven	Reduced distal mass and inertia, enhanced agility, remote/ centralized actuators	Transmission losses, complexity in cable maintenance and routing	High-speed, dynamic legged robots like Boston Dynamics Spot
Series Elastic / Compliant	Shock absorption, energy storage/recycling, increased safety	Complex control, potential delay in response	Impact mitigation tasks, wearable robots, agile locomotion

In robotic leg systems, transmission choice is critical for performance optimization [4], [5], [8]. Direct drive systems mount the actuator directly at the joint, offering excellent control precision and minimal latency in force transmission, but at the cost of increased mass at the leg's distal segments, which leads to higher inertia and reduced agility [4], [5], [10]. Cable or belt-driven transmissions relocate heavy motors closer to the robot's body, reducing distal mass and inertia and thereby enhancing leg swing speed, responsiveness, and overall agility [1]. These systems, however, introduce complexity in cable tensioning and potential energy losses due to friction and elasticity [1], [8]. Series elastic or compliant mechanisms incorporate elastic elements like springs into the drivetrain, providing valuable shock absorption, energy storage, and safer interactions with the environment by buffering impacts [3], [12]. While these elastic components improve durability and efficiency, they complicate control due to the inherent compliance introducing response delays [12]. Variable stiffness designs, including VSSEA-type architectures, address this limitation by allowing the robot to tune stiffness in real time for the task: soft and compliant for safety, impact tolerance, and physical interaction, or stiff and high-bandwidth for precise tracking and high-force maneuvers and they can do this with fast stiffness modulation, wide stiffness range, high torque density, and low energy cost at equilibrium [12], [16]. Each mechanism shows strengths and limitations as shown in Table-1 direct drive excels in precision, cable/belt drives optimize agility and mass distribution, and compliant/variable-stiffness transmissions enhance safety, impact robustness, and energetic efficiency[10], [12], [16]. The best choice depends on the robot's size, intended speed, environmental interactions, and control sophistication, with modern cable-driven and variable-stiffness compliant legs offering a practical compromise for agile, dynamic legged robots that must both absorb shocks and deliver high-performance in unstructured terrain [1], [4], [16].

III. Variable Stiffness Actuators (VSA)

VSAs embody a hybrid approach that combines the compliance benefits of SEAs with the active controllability needed for highly versatile and robust robotic movement [16]. Variable Stiffness Actuators (VSAs) fundamentally enable robotic joints to adjust their mechanical stiffness actively and independently of position [14], [16]. This is primarily achieved through mechanisms such as adjusting spring preload where the initial compression of a spring changes the joint's geometric transmission ratios to modify force translation, employing antagonistic actuation that mimics biological muscle pairs, or varying the effective length of springs in designs like leaf springs [15], [16]. Such modulation allows the robot to switch between soft compliance and rigid support as needed, enhancing adaptability and safety in interaction [16].

VSAs also contribute significantly to energy efficiency [16]. By storing elastic potential energy when compressed or stretched, these actuators can rapidly release stored energy to assist motions like jumping or hopping, similar to biological muscles and tendons [30][15]. This energy recycling reduces the active power demand on motors and can enable more natural and dynamic locomotion patterns [16]. Advanced VSA designs ensure that during equilibrium positions, the stiffness modulation consumes minimal power, thus optimizing overall energy usage during repetitive tasks and interactions [16].

This combination of adjustable mechanical compliance and energy-efficient operation makes VSAs key elements in next-generation agile robotic systems, particularly legged robots that require versatility, safety, and performance in unstructured environments [3], [16].

A. VSA Design Principles

1. Antagonistic VSA Principle

The antagonistic VSA principle is inspired by the biological muscle architecture, where pairs of muscles act in opposition around a joint to control both position and stiffness [12], [17]. Typically, two motors independently drive nonlinear elastic elements arranged as agonist and antagonist springs on either side of the joint [12], [16]. By co-contracting the springs (driving the motors toward each other), the effective joint stiffness increases because both springs generate opposing forces that balance each other but increase resistance to external perturbations [12], [17]. Conversely, relaxing these springs decreases the stiffness, allowing compliant interaction with the environment[12], [17]. This architecture provides a broad and continuous range of stiffness modulation, high fidelity in stiffness control, and improves force feedback fidelity due to the balance of antagonistic forces [12], [16]. However, this design inherently demands two actuators per joint, which increases overall system weight, complexity of mechanical integration, and power consumption, potentially limiting its application in size- and energy-constrained platforms [12], [17].

2. Adjustable Pretension VSA Principle

This principle utilizes a single elastic element (often a spring) whose pretension is actively controlled by changing the spring's attachment position or compression via a mechanical module such as cams, slider mechanisms, or linear actuators [12], [16], [17]. The pretension adjustment alters the equilibrium length of the spring, effectively changing its operating stiffness [12], [16]. This approach simplifies the mechanical design by requiring fewer actuators than antagonistic systems, reducing weight and volume [12], [17]. The tradeoff is a narrower achievable stiffness range compared to antagonistic setups and a slower response time since mechanical movement is required to vary the preload [16], [17]. Furthermore, the nonlinear behavior of the spring's force–displacement relationship can complicate the control strategy, necessitating advanced algorithms to achieve smooth and stable stiffness modulation [12], [17].

3. Geared Elastic VSA Principle

In geared elastic actuators, elastic elements are integrated within the gearboxes or transmissions, enabling modulation of stiffness through changes in mechanical preload or the alteration of gear engagement angles [17]. These actuators allow compact integration of compliance and motion transmission in a single unit, often improving power density and actuation efficiency [10], [17]. Some mechanisms employ planetary gear sets or cam-based transmissions to vary the lever arm or effective stiffness [16], [17]. Although this approach offers high stiffness modulation ranges and efficient power transfer, the introduction of gearing complexity often brings challenges such as backlash and increased friction [1], [7], [10]. These can degrade position accuracy and introduce hysteresis, requiring careful mechanical design and control compensation [10].

4. Cable-Driven VSA Principle

Cable-/belt-driven transmissions route tensile elements over fixed/movable pulleys to convert motor rotation into joint motion with leverage; antagonistic winch paths provide clean rotary output, large travel, and built-in reduction (≈1:12 in tensegrity joints) [3]. By routing through a central shaft and pulley blocks, heavy actuators can be mounted off-joint to cut distal mass and simplify integration [13], [14]. In belt variants, correct pretension is critical non-backdrivable screws/worms hold settings safely; too little causes slip, too much limits travel/overloads the belt defining a reliable operating window [15]. Pulley blocks can also convert rotation to linear spring compression, letting one routed cable drive multiple compliant units within compact actuator modules [13].

5. Magnetorheological (MR) Fluid-Based VSA Principle

MR fluid or elastomer-based VSAs leverage the rapid change in the material's rheological properties when subjected to a magnetic field controlled via coil current [2], [12]. By integrating MR substances inside the actuator, the effective joint stiffness can be dynamically tuned with high bandwidth and relatively simple hardware, advantageous for robotic systems requiring fast compliance adaptation [2], [12]. These MR-based VSAs can provide large ranges of stiffness and offer damping benefits, improving performance in dynamic tasks [2], [12], [17]. Nevertheless, they add weight due to electromagnetic components and continuously consume power to maintain the magnetic field [9.pdf p.459]. Long-term reliability can be affected by hysteresis and aging effects of the MR materials, posing maintenance consideration [2], [17].

Each VSA principle balances unique advantages and inherent material or mechanical limitations [12], [16], [17]. Designing an effective VSA often involves trade-offs between stiffness range, actuation complexity, speed of modulation, energy consumption, and mechanical robustness [12], [16], [17]. For example, antagonistic architectures excel in range and accuracy but suffer from size and complexity [12], [17], while single-element preload methods offer simplicity but limited bandwidth [16], [17]. Geared VSAs offer dense packing but can introduce backlash [10], [17], [18]. Cable-driven systems enhance distal agility but involve complex tension management [1], [6], [8]. MR fluid-based designs provide fast responsiveness with an energy trade-off [2], [12]. The optimal choice depends on the specific robotic application's performance requirements and design constraints [4], [5], [8], [17].

B. Various VSA Configuration

1. Tensegrity-based VSA

The variable stiffness actuator (VSA) mechanism developed by Erik Mortensen et al. works by physically tuning how stiff or compliant each leg joint is, instead of keeping stiffness fixed or faking it in software. The leg uses two single-DoF tensegrity joints (hip and knee), each built from PET-G structural connectors and a Tristar pivot that are held together with pre-tensioned elastic tendons. This tensegrity layout gives passive compliance the joint can give under load but the geometry still constrains motion mostly to one clean rotation axis rather than wobbling in multiple directions. Motion at each joint comes from an antagonistic cable pair: a winch servo pulls one cable and releases the other, and the cables are routed over pulleys in the Tristar so that servo rotation turns into joint rotation with an effective ~1:12 mechanical reduction (5 mm drum radius to 60 mm joint pulley radius). Stiffness itself is not passive or constant: both joints are linked to a shared VSA module in the femur. A stepper motor drives a T8 lead screw, sliding a carriage that increases or relaxes cable pre-tension through a staged spring system as shown in fig. 4. By shifting that slider, the robot can command "softer" or "stiffer" joint behaviour on demand, because the rotational stiffness of the joints directly depends on that pre-tension level [3].

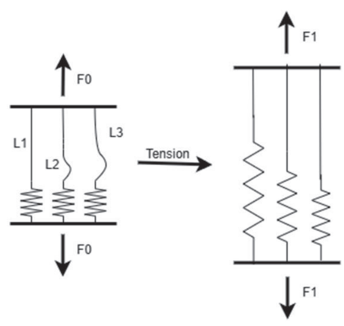

Fig.4. Working principle of the multi-spring system to achieve quadratic stiffness behavior.

In terms of specs and features, the leg is roughly human scale, with pelvis, femur, and tibia links plus the two tensegrity joints, and reaches about 0.83 m in its extended configuration. Each joint can sweep about 175° total (≈ −30° to 145°), which is unusually large for a compliant joint, and the structure is reinforced with aluminium tubes and pre-tensioned TPU 95 tendons so it keeps its shape under load while still staying compliant. Joint actuation uses an off-the-shelf Kingmax SW5513-6MA winch servo, which can deliver around 1.042 N·m and is rated for very large travel (up to 2160°); with the ~1:12 cable leverage, this is enough to statically hold a 1 kg load at a worst-case 0.83 m lever arm from the hip. The stiffness module is centralized instead of duplicated per joint: a Minebea-Mitsumi PG25L-D24-HHC1 stepper drives a 100 mm T8 lead screw (S SIENOC) that moves a PET-G slider to tension both hip and knee tendons at once, rather than mounting a separate stiffness motor at each joint. That slider ties into three stainless-steel tension springs (≈35 mm long, ~4.9 mm diameter, ~0.7 mm wire, ≈388.4 N/m each). The springs are attached with staggered cable lengths so they “engage” in stages first one spring, then two after ~12 mm more pull, then all three after ~36 mm which produces a nonlinear, almost quadratic stiffness curve with $R^2 \approx 0.9983$ instead of just one fixed spring constant [3].

This VSA architecture gives three main advantages. First, the robot can mechanically dial joint stiffness in real time soft for compliance or impact tolerance, stiff for support and control just by changing pre-tension through the shared spring/lead-screw module, with no hardware swap. Second, each tensegrity joint still behaves like a clean hinge with ~175° usable motion, which makes control easier than classic tensegrity joints that tend to move in coupled, hard-to-model ways [3]. Third, putting one stiffness unit in the femur that services both joints keep mass and complexity down compared to giving every joint its own VSA hardware. The paper also states the main limitations: routing antagonistic cables through pulleys introduces friction and torsional effects that distort the “ideal” stiffness response and can create oscillations; sensing is still minimal (no integrated joint encoders, force/torque sensing, or IMU feedback in the loop); and the current actuation bandwidth and control approach are not yet tuned for fully dynamic walking. The authors point out that future versions will need cleaner tendon routing, higher-performance actuators (e.g. brushless or pneumatic muscle-type), and closed-loop sensing/control before this can be dropped into a fast-legged robot [3].

2. VSA Based on Cable-Pulley-Driven Mechanisms

Zhisen Li, Peng Xu, and Bing Li present a compact variable stiffness actuator (CVSA) changes joint stiffness mechanically by preloading springs through a cable–pulley transmission rather than relying only on motor current or software to imitate compliance. Each stiffness unit is a crank–slider with two sliders and a spring shown in fig.5, when the joint deflects, the linkage compresses the spring and produces an elastic torque that passively resists external disturbance. Stiffness is actively adjusted by moving a second slider that preloads the spring via a routed cable (fixed pulleys plus a movable pulley on the slider). Pulling the cable increases preload → higher stiffness; releasing it lowers preload → softer joint. Multiple identical stiffness units can be placed in parallel and driven by a single stiffness-adjusting motor, so the overall stiffness range is scalable just by changing how many units you install. The mechanism is laid out so motor rotation becomes linear compression of the springs, and the output passes through a passive plate and output cap that deliver joint torque while allowing angle and torque measurement through encoders and a torque sensor [13].

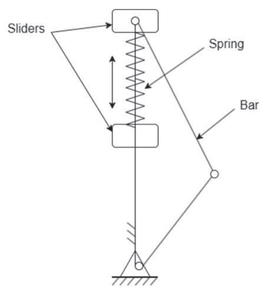

Fig.5. Principle of the CVSA.

Physically, the actuator is organized into three modules: (i) the drive module, which combines a position motor, reducer, brake, encoder, and servo driver; (ii) the variable stiffness module (VSM); and (iii) the output/measurement module, which includes the output cap, a hollow absolute encoder, and a torque sensor. In the prototype, the VSM uses three stiffness units (N = 3) and is very compact: ~110 mm max diameter, 49 mm VSM length (without motors), ~0.46×10^{-3} m³ VSM volume, and about 2.6 kg total mass. The actuator supports a wide motion range (±180°) and delivers high nominal torque (~31 N·m), giving a torque density on the order of 6.75×10^{4} N·m/m³, which is high compared to many existing VSAs despite the small package. A key integration feature is that the stiffness-adjusting motor doesn’t need to sit at the joint: the stiffness cable is routed through pulley groups and even through a central bore in the shaft, so that motor can be mounted remotely (e.g., elsewhere on the robot frame or on the user’s body in an exoskeleton), keeping the joint itself lighter and less bulky. The system also includes sensing (20-bit hollow absolute encoder and output torque sensor) and uses an improved active disturbance rejection controller (IADRC) with adaptive online tuning to maintain position tracking under load, under stiffness changes, and under disturbances [13].

The main benefits are: (1) tuneable stiffness range overall stiffness can be increased by adding more stiffness units in parallel and driving them with the same cable; (2) compact packaging at the joint because stiffness regulation can be done remotely through the routed cable and through-shaft path; (3) fast response, with stiffness able to drop in roughly 0.24 s after an impact to limit collision torque; and (4) accurate tracking under load thanks to the IADRC control scheme, which stays stable even while stiffness is being actively changed [13]. The limitations noted are: friction, clearances, and damping introduce hysteresis and cause the measured torque–stiffness curve to deviate from the ideal model; the absolute stiffness range still needs to be pushed further; and full integration into a complete robotic limb or human-interactive system is future work, not yet demonstrated in a full robot.

3. Biomimetic variable stiffness actuator (BVSA)

Yaowei Song et al. have developed actuator is a biomimetic variable stiffness actuator (BVSA) inspired by human skeletal muscle, where joint stiffness is adjusted continuously by changing cable tension instead of relying on two opposing motors or swapping mechanical springs [19]. Structurally, the BVSA is built as a compliant mechanism made of two parallel elements: a positive stiffness element (PSE) and a negative stiffness element (NSE). These two elements work together to emulate how real muscle tendon systems behave: they generate force, provide compliance, and let stiffness be regulated smoothly rather than in discrete steps. By controlling the tension in the drive cable, the actuator can “dial in” how stiff or soft it is at any moment, so stiffness becomes a controllable parameter rather than a fixed property. The Schematic of the skeletal muscle biomimetic design is shown in fig.6 The paper also develops a mathematical model for this actuator using biomechanical analysis, a pseudo-rigid-body model (PRBM), and elliptic integral methods, so the stiffness characteristics are not just qualitative but can be predicted, tuned, and controlled [19].

The BVSA is designed to be compact, lightweight, low-friction, and manufacturable, while still covering a wide adjustable stiffness range, directly addressing the size, complexity, and mass penalties of traditional VSAs that preload springs with two coordinated motors. Its force–displacement curve is shaped through geometry so that the actuator first behaves with very low or near-zero stiffness, and then stiffness increases in an almost linear way as displacement grows. That means the same actuator can start gentle and compliant, then provide more support under load, similar to biological muscle response. After optimization, the final parameter set (M = 1, N = 3, ln = 35, γ = π/36, x = 8, y = 0.5) is chosen to balance three goals at once: a compact structure, a useful low-stiffness region, and a broad tuneable stiffness window. The authors compare analytical results and ANSYS simulations and show close agreement in both the force–displacement and stiffness curves, with only limited deviation in part of the range (particularly for dn between about 0.1 and 0.8), which indicates the concept is physically realizable and not just theoretical [19].

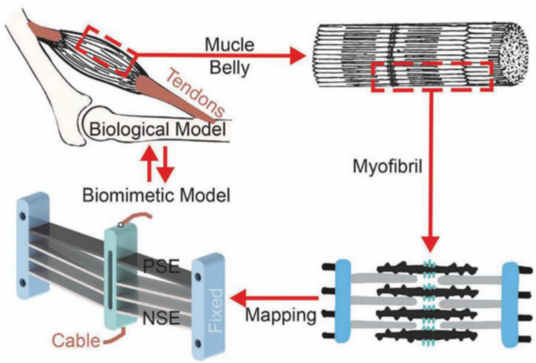

Fig.6. Schematic of the skeletal muscle biomimetic design [19].

The main advantages of the BVSA are: (1) it targets muscle-like, continuous stiffness modulation using cable-tension control instead of heavy antagonistic actuators; (2) it can provide an intentional "soft-contact" or near-zero stiffness zone for safe initial interaction, then smoothly ramp into supportive stiffness as loading increases useful for assistive, medical, and humanoid joints; and (3) it aims for low mass, low friction, and structural simplicity compared to many conventional variable stiffness actuators. The limitations are also clear. Changing geometric design parameters (for example γ) shifts both where the force–displacement curve starts and how steeply it grows, so you cannot independently tune load capacity and stiffness behaviour — they are coupled and must be co-designed . In addition, while the BVSA has been modelled and validated in simulation, it has not yet been fully integrated and tested on a physical multi-DoF robot. The planned next step is to mount it on a 7-DOF cable-driven humanoid arm (shoulder, elbow, wrist) and evaluate real-time stiffness regulation in hardware, but that full experimental integration is still future work [19].

4. Permanent magnetic mechanism (PMM) VSA

Zhang et al. present a novel cable-driven variable-stiffness joint (VSJPMM) that uses two antagonistic wire paths and a permanent magnetic mechanism (PMM) to achieve both compliance and high torque, similar to how flexor and extensor muscles co-act in a human limb. Two symmetric cables pull on the joint arm through pulleys; by adjusting cable tension, the joint both rotates and changes stiffness. The PMM uses two coaxial ring magnets with like poles facing each other, so they repel. One magnet slides like a "magnetic spring." A movable pulley links this sliding magnet to the cable path: when the cable is pulled, the air gap between magnets shrinks, the repulsive force rises, and the effective joint stiffness increases in a nonlinear way without needing extremely high cable tension like classic spring-preload VSAs [14]. The paper models how motor rotation, cable stretch, and the PMM force translate into output torque and equivalent rotational stiffness, and uses that model to build a controller that can command joint angle and stiffness independently instead of them interfering with each other.

Physically, the joint is packaged in a trapezoidal layout so the PMM, pulleys, and motors sit behind the arm instead of directly on the rotation axis, keeping the moving mass low for multi-DoF robots. Each cable runs from the arm, through a V-groove pulley, through the PMM, and then to a winch, forming a mirrored antagonistic pair; a shaft encoder provides joint position for feedback and stiffness estimation. The hardware is compact: ~60 mm axial length, ~60 mm radius, ~0.3 kg moving mass (without motors), and a usable motion range of about −70° to +70° (with ~20° tested in stiffness evaluation) [21]. The joint can vary stiffness from about 1.3 to 239.8 N·m/rad (with Kevlar rope) and can change stiffness in ~0.4 s, while staying up to ~69–92% lighter in moving parts than several compared variable-stiffness designs such as PVSA, AwAS, and vsaMGR. A decoupling controller uses the analytical stiffness model and solves for the required cable stretch (via Newton's method) so that it can track both a target angle and a target stiffness at once; experiments show ~1.2% position error and ~8.9% stiffness error [14].

The main advantages are: (1) lower energy cost, because the magnetic repulsion plus pulley geometry lets the joint hold stiffness with less cable tension and therefore lower motor current in tests, steady-state energy demand dropped to ~50–66% of comparable spring-based systems; (2) independent stiffness and position control, so the joint can "go soft" or "go stiff" without changing pose; (3) fast stiffness modulation over a wide range in ~0.4 s, enabling both safe, compliant contact and high-torque behavior on demand; and (4) high stiffness range in a compact, low-mass module suitable for robot arms or humanoid joints. Limitations include: ultimate stiffness is limited by cable strength (Kevlar vs steel rope matters); mechanical friction, tolerances, and backlash create hysteresis and small gaps between predicted and measured stiffness curves; tracking degrades at higher motion frequencies (up to ~10% error); and full multi-joint deployment (e.g., as a full humanoid elbow with full impedance control) is still future work, not yet demonstrated as an integrated system [14].

5. Variable Stiffness Series Elastic Actuator (VSSEA)

Sariyildiz et al. present a Variable Stiffness Series Elastic Actuator (VSSEA). It has three functional subsystems: (1) a standard high-torque drive (motor + gearbox) that positions the joint, (2) a variable stiffness module (VSAM), and (3) a separate direct-drive motor dedicated to adjusting stiffness without changing joint angle.

The CAD model of leaf springs and mobile frame of the VSAM is shown in fig.7. The VSAM consists of eight leaf springs mounted radially in parallel, each carrying a pair of rollers. A ball screw repositions these rollers along the springs. Shifting the rollers changes the effective free length of each spring, which changes how much it resists bending. When the rollers are closer to the spring tips, the joint behaves very compliant; when the rollers are moved toward the fixed bases, the joint becomes much stiffer. Because motor M2 moves the rollers (and therefore sets stiffness), while motor M1 sets the joint angle, stiffness and pose are independently controllable. As a result, the same joint can act like a soft, shock-absorbing series elastic actuator or like a rigid, load-bearing joint and it can switch between those behaviours on demand without redesign and without sacrificing motion range [16].

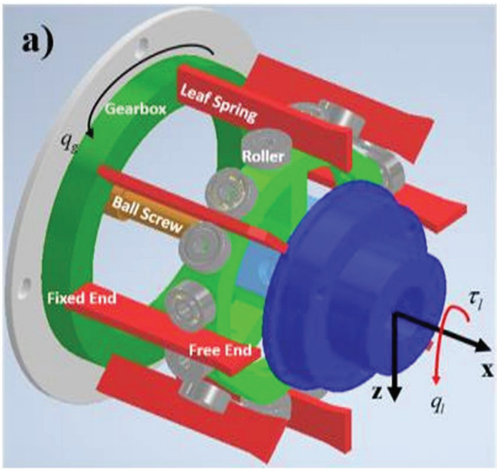

Fig.7. CAD model of leaf springs and mobile frame of the VSAM [16].

The VSSEA targets several performance goals simultaneously: very large stiffness tunability, high output torque per unit mass, rapid stiffness adjustment, low steady-state power cost, and no artificial limit on the joint's travel. In experiments, effective joint stiffness can be varied from roughly ~20 N·m/rad to ~1000 N·m/rad (for example, ~21 N·m/rad in its softest state vs ~985 N·m/rad in its stiffest), which is about a 50× swing, and stiffness can change extremely fast on the order of ~3000 N·m/rad/s even when the joint is not at its equilibrium position [16]. On the drive side, the prototype uses a Maxon EC90 flat motor with a 1:100 harmonic drive (this is motor M1), giving on the order of 100 N·m output torque and about π/2 rad/s output speed, with an overall torque density around 36 N·m/kg, which is suitable for high-interaction systems like collaborative arms, wearable assist devices, and leg modules. Energy usage is a major design point: once the rollers are placed on the springs, the chosen stiffness "holds" passively and motor M2 does not need to continuously draw current to maintain it. Even when changing stiffness, the added work from M2 stays bounded and relatively small compared to the elastic energy stored in the springs at small deflections. Importantly, despite the nonlinear mechanics, the actuator can still be run using straightforward PID control for both position and force tracking, rather than needing complex adaptive or learning-based control, which is uncommon for compliant, variable-stiffness systems [16].

The authors highlight that VSSEA combines, in one package, capabilities that usually appear only separately in earlier variable stiffness actuator designs: (1) true decoupling of position and stiffness motor M1 sets where the joint is, motor M2 sets how stiff it is, and you can change one without disturbing the other; (2) extremely wide and fast stiffness modulation, from very soft toward effectively very stiff, without sacrificing range of motion; (3) low or near-zero holding cost for a commanded stiffness, and bounded energy to adjust stiffness even off-equilibrium; and (4) high torque density in a modular architecture that can be reconfigured (e.g., by selecting different gear ratios, spring geometries, or ball screw leads) for different robot use cases, from cobots to leg joints to exoskeleton support. The paper also lays out the current limitations. In the low-stiffness setting, the joint is easier to disturb and maintaining precise high-bandwidth position control becomes harder; in the high-stiffness setting, physical safety in contact is reduced. The modelling is split between a large-deflection nonlinear beam model (very accurate but computationally heavy) and a small-deflection approximation (faster but less accurate at high deflection), so unified real-time modelling across the entire range is not yet solved. Finally, while the prototype shows fast transitions between "soft" and "stiff" (on the order of under a second) and good PID-based tracking, automatic mode switching between safe-interaction behaviour and precision-hold behaviour, and full deployment on whole systems like legged robots, are presented as future integration work rather than complete, field-ready capability [16].

6. Variable stiffness floating spring leg mechanism

Kim et al. introduce a "floating spring leg" is a quasi-passive assist leg with variable stiffness. It can change how stiff it is even after the spring is already compressed and storing energy, which normal fixed-stiffness springs cannot do. The system is built from three main parts: a multi-DOF leg structure (hip–knee–ankle style), a mechanism (shown in fig.8) that repositions the spring attachment points on the links, and a compression spring that can be locked and later released. Its operating cycle is: (1) compress and lock the spring at a low-stiffness configuration to store energy, (2) slide both ends of that locked spring along the leg to a geometry with higher leverage and thus higher effective stiffness and output force, and then (3) unlock and release the same stored energy at this higher-stiffness configuration to generate assistance, e.g. to help stand up or lift a load. This lets the leg deliver a stronger push on demand without adding new energy at the moment of assist, because it's reusing energy that was already stored earlier [20].

The prototype is a 5-DOF lower-limb-like mechanism with hip, knee, and ankle-style joints (including ankle pronation/supination) so it can push through a foot like a human leg segment. Stiffness is adjusted by moving the spring's endpoints using two lockable sliders on the links: a motorized lower slider and a passive upper slider. These sliders grab the structure using brake levers and friction pads under load, and only reposition when the spring is locked and unloaded. A bowstring-style linear actuator (48 W brushless DC motor and Kevlar cable with encoder feedback) drives the lower slider. Repositioning the sliders while the spring is locked costs very little power, and once the sliders are clamped in place and the spring is loaded, no holding power is needed to maintain that stiffness setting [29]. The spring module uses a die spring plus a friction clutch so it can be compressed, locked, and later released; it weighs ~1.9 kg, has stiffness ~14.8 N/mm, can generate >1200 N force, and returns ~80% of stored energy after losses [20]. In a demo, the leg helped lift a 27 kg load in a squat-to-stand motion by charging the spring at low stiffness, then switching geometry to high stiffness without adding energy, and finally releasing at high stiffness for a stronger assist.

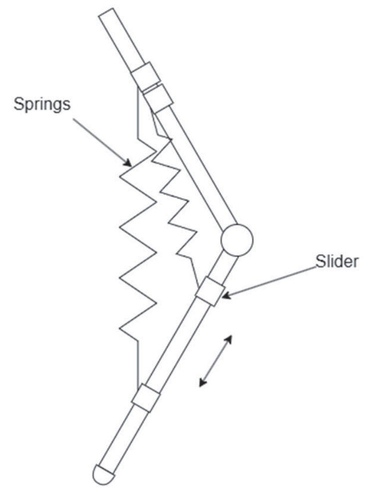

Fig.8. Floating variable stiffness spring mechanism.

This approach offers two major benefits: it behaves nearly like a passive spring in terms of net energy cost over a full assist cycle, and it can still boost peak assistive force right when it's needed by increasing effective stiffness just before release. That makes it appealing for tasks like standing assistance or vertical lifting with minimal external power, since the only active input is the relatively low-power repositioning of the spring endpoints. At the same time, there are trade-offs. The mechanism is more complex and heavier than a plain spring: it needs a reorientation motor, two locking sliders, and a lockable/clutched spring module, and the overall leg frame is still relatively heavy (around three times the spring module mass). Some energy is still required to shift stiffness, and the authors note that real-world wearable use will need weight reduction, better human fit/comfort, and possibly added elements like a knee clutch before it can function as a practical multi-DOF exoskeleton-style assist device outside the lab [20].

7. *Variable-length leaf-spring actuator (VLLSA)*

Sajiv Shah et al. present a compact actuator (SiMPLeR) which is a low-cost series elastic actuator with adjustable stiffness. It uses two belt–spring paths arranged antagonistically, like opposing muscles, with torsion springs attached to a timing belt shown in fig.9 below. When the joint deflects, those springs create a restoring torque through the belt, like a normal SEA. But unlike a normal SEA with fixed springs, SiMPLeR can change stiffness by changing the distance between the motor and the joint: increasing that distance increases pretension in the springs (stiffer joint), and decreasing it relaxes the springs (softer, more compliant joint). This gives the actuator two independent inputs motor angle sets joint position, and motor–joint separation sets stiffness so torque depends on both deflection and a tuneable stiffness parameter that can be held without constantly feeding power [15].

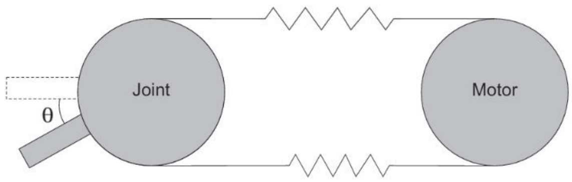

Fig.9. Drawing of Series Elastic Actuator with linear springs [15].

Structurally, the design is intentionally simple and cheap. Standard torsion springs are reused so that their rotational stiffness becomes belt tension, producing a nonlinear stiffness profile that can be adjusted just by changing pretension instead of swapping custom elastic elements [30]. A secondary mechanism (e.g. an acme screw) repositions the motor relative to the joint to set that pretension. Because the screw driver can be made non-back drivable, once you pick a stiffness it "locks in" with basically no holding power, and it won't collapse even during a power loss important for robot legs that need to keep standing. The model in the paper shows how joint torque τ depends on both joint deflection θ and pretension. High pretension makes the joint stiff and load-bearing; low pretension makes it compliant and energy-absorbing. There's a usable middle range: too little pretension and the belt slips, too much and you're nearly rigid, risking belt overload and reduced travel. In that middle band, stiffness can be tuned for tasks like landing, standing, or hopping without changing hardware [15].

For legged robots, the appeal is that this gives you a leg that can act rigid for high-force behaviours (fast hopping, supporting weight) or soft for impact safety and uneven terrain and you can switch between those modes with pretension, not by swapping actuators or running high-bandwidth active impedance control. The actuator can also hold a chosen stiffness passively with almost no power draw, and the paper shows it can shape landing response (reduce oscillations after touchdown) and support both gentle, low-speed hopping and aggressive, high-stiffness hopping using the exact same mechanism, just at different pretension levels. The trade-offs are: very low pretension risks belt slip and loss of precise force control; very high pretension risks belt skip under impact and limits allowable motion; the springs sit in the belt path so the joint can't rotate indefinitely; and mechanically it's still bulkier than a fixed-stiffness SEA because of the extra screw/slider hardware to move the motor. Full multi-joint integration is still future work, but overall SiMPLeR is presented as a practical, scalable passive variable-stiffness approach using mostly common parts instead of exotic custom actuators [15].

TABLE 2. COMPARATIVE TABLE OF VARIABLE STIFFNESS ACTUATORS (VSAS)

Name / Reference	Actuation Method	Mechanism Complexity	Stiffness Range	Size / Weight	Max Torque	Stiffness Modulation Speed	Notable Features / Others
Tensegrity-based VSA Yu et al.	Leaf-spring with ball screw slider	Moderate (leaf spring, slider, gear set, ball screw)	0 – 1787 Nm/rad	180×40×40 mm, 0.45 kg	-	2961.7 Nm/(rad·s)	Compact, lightweight, energy-efficient, fast modulation, fits narrow spaces
Cable-Pulley VSA Li et al.	Cable-pulley, crank-slider, spring preload	Moderate-High (multiple VSMs, pulleys, remote motor)	38.7 – 87.2 Nm/rad	0.46×10^{-3} m^3, Ø110 mm, 2.6 kg	31 Nm	0.24 s (full range)	Modular, remote motor, high torque density, fast response
Biomimetic VSA (BVSA) Song et al.	Kevlar cable, composite compliant (PSE+NSE)	Moderate (composite beams, cable tension)	Wide, continuous (zero-stiffness region)	Compact, lightweight (epoxy+Kevlar)	-	Infinitely adjustable	Biomimetic, zero-stiffness, smooth/linear adjustment, vibration isolation
Permanent Magnetic Mechanism (PMM) VSA Zhang et al.[2]	Wire-driven, permanent magnet spring	Moderate (antagonistic wires, PMM, pulleys)	1.3 – 239.8 Nm/rad	60 mm (L) × 60 mm (R), 0.3 kg	-	0.4 s	Low energy, compact, independent position/stiffness, fast modulation
VSSEA (Series Elastic) Sariyildiz et al.	Leaf springs, ball screw, direct drive	Moderate-High (8 leaf springs, rollers, ball screw)	20 – 1000 Nm/rad	Not specified, 36 Nm/kg torque density	-	<1 s (full range), up to 3000 Nm/rad/s	Modular, high torque density, low energy, fast, continuous modulation

Floating Spring Leg Kim et al.	Axial compression spring, motorized sliders, clutch	High (5-DOF, lockable spring, sliders, clutch)	Up to 14.8 N/mm	Spring: 1.9 kg, Leg: 6.3 kg	>1200 N force	Rapid (independent of stored energy)	Net-zero energy, force amplification, 80% energy return, complex integration
Variable-Length Leaf-Spring Actuator (VLLSA) Yu et al.[4]	Leaf spring, ball screw, gear set	Moderate (leaf spring, ball screw, gear, linear guide)	9.43 – 22.55 N·m/rad (exp.), theoretically infinite	180×40×40 mm, 0.45 kg	-	0.2–0.35 s	Compact, lightweight, energy-efficient, precise, real-time control

CONCLUSION

Variable Stiffness Actuators (VSAs) are redefining legged robotics by giving robots the ability to actively tune how stiff or compliant their joints and limbs are during motion. This directly tackles the core limits of conventional rigid, high-torque legs, high impact loads, high control burden, high distal inertia, and poor adaptability to unpredictable terrain. With VSAs, a leg can be soft and compliant for shock absorption, terrain safety, and human interaction, then rapidly become stiff and load-bearing for support, jumping, lifting, or precise force transfer.

The reviewed actuator families each deliver this adaptability in different ways. Compact leaf-spring and tensegrity-style VSAs (including VLLSA) fit inside a limb segment while offering fast, wide-range stiffness modulation. Cable–pulley and series-elastic designs like CVSA and VSSEA decouple joint angle from stiffness, reach high torque with very large stiffness ranges, and can switch stiffness in fractions of a second while holding that stiffness with little or no steady-state power. Biomimetic and magnet-based designs (BVSA and VSJPMM) enable safe, muscle-like behaviour: near-zero stiffness for gentle contact, then controlled stiffening under load, with low moving mass and independent control of position and stiffness. Task-level systems such as the floating spring leg and SiMPLeR go further, reusing stored elastic energy and mechanically "re-gearing" stiffness to deliver assistive force for standing, lifting, or hopping with minimal extra energy. The key change is that stiffness is no longer fixed in hardware it's now an actively controlled variable, like position and torque. This makes next-generation legged robots stronger, safer, more energy-efficient, and better able to adapt to real-world human environments.

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