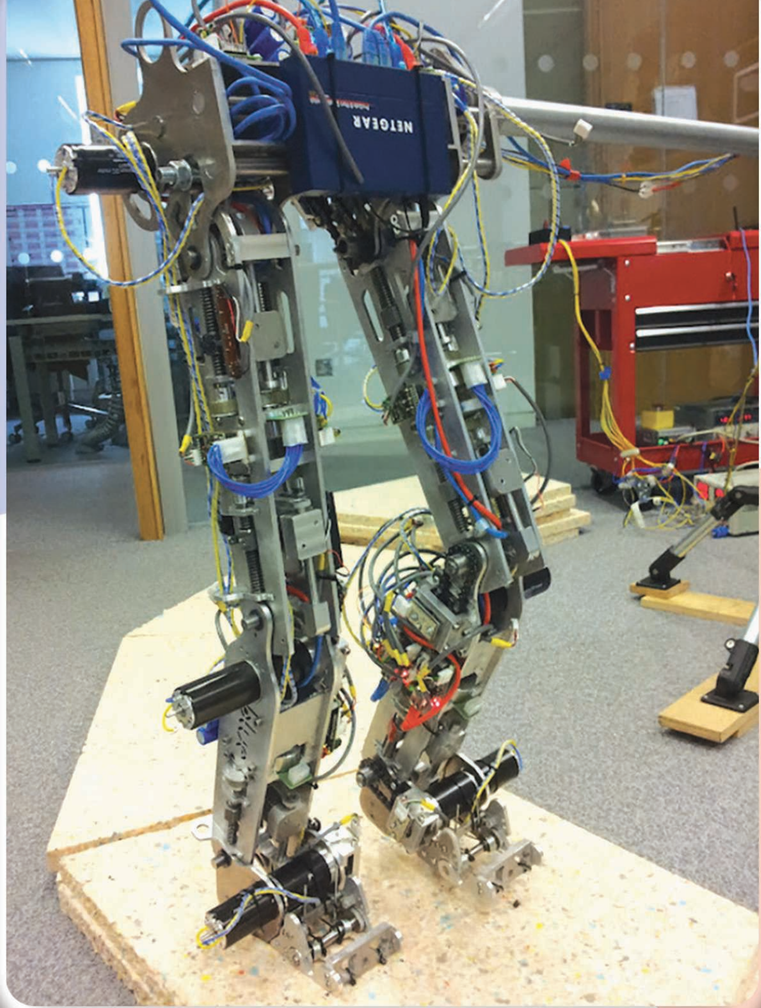

A Review

Damping in Compliant Actuation

By Simone Monteleone, Francesca Negrello, Manuel G. Catalano, Manolo Garabini, and Giorgio Grioli

Compliant actuator technology aims at building robots capable of physically interacting with humans and the environment, matching the versatility and capacity of biological systems. Recently, it underwent a significant evolution with the introduction of damping to improve performance. Such development reflects several aspects, including energy saving and oscillation mitigation. However, large damping values tend to increase the system impedance, worsening robot resilience and human safety during impacts. That suggests the importance of a correct tradeoff.

This article reviews the application of damping solutions to compliant actuation. We classify damper systems based on the amount of active control, their physical operation principle, and the topological position of the damping element used

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in the various actuators. Then we study the fields of application of these devices and analyze how different design aspects correlate with one another and applications. This analysis yields insight into how design choices can influence the characteristics of actuators and the robots using them, from the viewpoint of robot resilience, human safety, power consumption, and energy storage. Finally, we provide an annotated database of the papers considered to conduct this review.

Overview

The field of compliant robotic actuation has been growing [1], [2], motivated by the intention of building robots able to cope with unknown environments [3], behave safely in human–robot interaction [4], tolerate shocks [5], store energy [6], [7], and move agilely on legs [8]–[10]. Nevertheless, when compared to rigid equivalent robots, compliant actuation underperforms in some domains. Among other aspects, reduced control authority bandwidth can lead to undesired oscillations and vibrations [11], which can, in turn, reduce precision, compromise stability, and waste energy. Through the years, it became clear that to mitigate such limitations [12], which can jeopardize the very advantage of using compliant actuation in the first place, the inclusion of some form of damping action [13] is mandatory.

A possible method to suppress vibrations is through active control [11], [14]. However, such an approach requires the actuator to move very fast and consume a lot of input power to stably dissipate the mechanical energy of the system [15], [16]. To overcome this, engineers began to include physical damping elements to recover system performance and facilitate stabilization [17]. They drew inspiration from the dynamic behavior of human muscles [18]–[20] and natural systems [21], [22] as well as technologies such as magnetorheological (MR) [23] and fluid dynamic [24] car suspensions, which are extensively studied in the automotive world [25]. This led to the proposition of actuators that combine soft behavior with engineered damping effects.

As shown by Figure 1(a), the interest in this topic arose almost 30 years ago, almost simultaneously with the birth of the first generations of compliant actuators. Nevertheless, studies of damped robotic actuators progressed slowly until the past 15 years, during which researchers began investigating the technology more thoroughly. This article acknowledges the maturity of the field by presenting a survey of damping technologies and their applications in robotic actuation. In particular, to narrow the breadth of our analysis and walk in the shoes of an actuator designer, we focus on solutions that include physical damping elements, referring the interested reader to [28] and [29] as access points to explore the vast literature on active control approaches to dampen compliant robots.

The first product of our analysis is a carefully crafted database of 50 research papers published during the past 30 years. These papers concern the design, use, and application of passive and semiactive damping in robotic actuation, describing 42 devices. The database categorizes the entries based on the design of the damping systems and their intended application. In particular, concerning damper design, the literature screening led to subdividing actuators according to the technology (i.e., the physical principle) they use to implement the damping action, their ability to change the damping ratio, and the connection topology of their architecture. While the first two classifications are commonplace in the robotic and automotive literature, the third, which is based on the possible ways to connect the main motor and its gearbox, the spring, and the damper (see the "Topology" section), is the second contribution of this article, which we hope will help guide the design and dissemination of future damped compliant actuators. The categorization based on intended applications is organized into two layers. The finer subdivision identifies 12 categories based on paper keywords. These are then grouped into three families based on a correlation analysis: medical haptic and wearable (MHW) robots, industrial and collaborative robots (ICRs), and humanoid assistive and legged (HAL) systems (see the "Applications" section). This grouping is also a result of our work.

The chronological study of the number of publications in each of these categories yields an important perspective in terms of research trends for design aspects and applications. Nevertheless, we derive the main results of our analysis by arranging the publications based on category pairs (see the "Discussion" section) to highlight relevant combinations among architectural aspects and application domains. We hope this review will provide a perspective on the past 30 years of research into using physical damping elements in the design of compliant robots and their actuators. We believe that our results could help future users of damped compliant robots understand the architectures of their systems and their motivations. Moreover, our approach aspires to guide future designers toward harnessing past insights and creating novel solutions.

Motivations

The optimal damping design for robots with soft actuators is not trivial to find since its inclusion is usually motivated by various, application-specific requirements. Often, one can narrow a task to yield the definition of a precise damping value. This is true for systems that exploit resonance and antiresonance to optimize cyclic tasks (e.g., hammering [30]) and cutting off band-specific vibrations (e.g., screwdriving [31]). But in general, most applications require the simultaneous optimization of several parameters of the task in question. As expected, not all these parameters behave in the same way as a function of the amount of damping.

Table 1 reports some notable examples of cost functions that are typically used to measure these parameters, showing how different their trends can be. We distinguish the effects of damping based on the architecture of the actuator (see the "Topology" section). The relative position of the main motor and its gearbox, the spring, and the damper affects the way damping interacts with the output and therefore the trend of the cost functions. Some cost functions, such as the overshoot percentage in row 1, which can be related to the accuracy of rapid motions of arms [32] and legs [33], tend to decrease with larger damping values until they reach a minimum and remain level. Nevertheless, it is worth noting how other parameters (e.g., the changing stiffness in the plots) influence the shape of the function and position of the plateau.

The behavior of the linear quadratic (LQ) cost in row 2, which is commonly used to design optimal LQ regulator control feedback [34], is similar to the previous one but not quite the same. For the most common actuator architectures, the LQ cost tends to decrease with larger damping values, although without reaching a plateau. Notably, in some architectures, the cost function has a minimum, which depends on the system stiffness. The presence of a definite minimum is a characteristic we meet again when looking at the maximum force transmitted by a robot in case of an unexpected impact, a critical factor for the safety of collaborative robots [35]. Nevertheless, if we look at the force transmitted to the actuator gearbox, which characterizes the impact resilience of a robot [36], the effect of the architecture topology can make it differ from the seemingly identical previous one (see the "Topology" section for an explanation).

Finally, not all cost functions improve with the introduction of damping. The last row of the table is a glaring example of this phenomenon, happening for the amount of energy dissipated during cyclic and rebound tasks. This parameter, which impacts the efficiency of walkers [37] and robots executing cyclic tasks in general, is destined to worsen with the addition of dissipative elements. An example of the complex

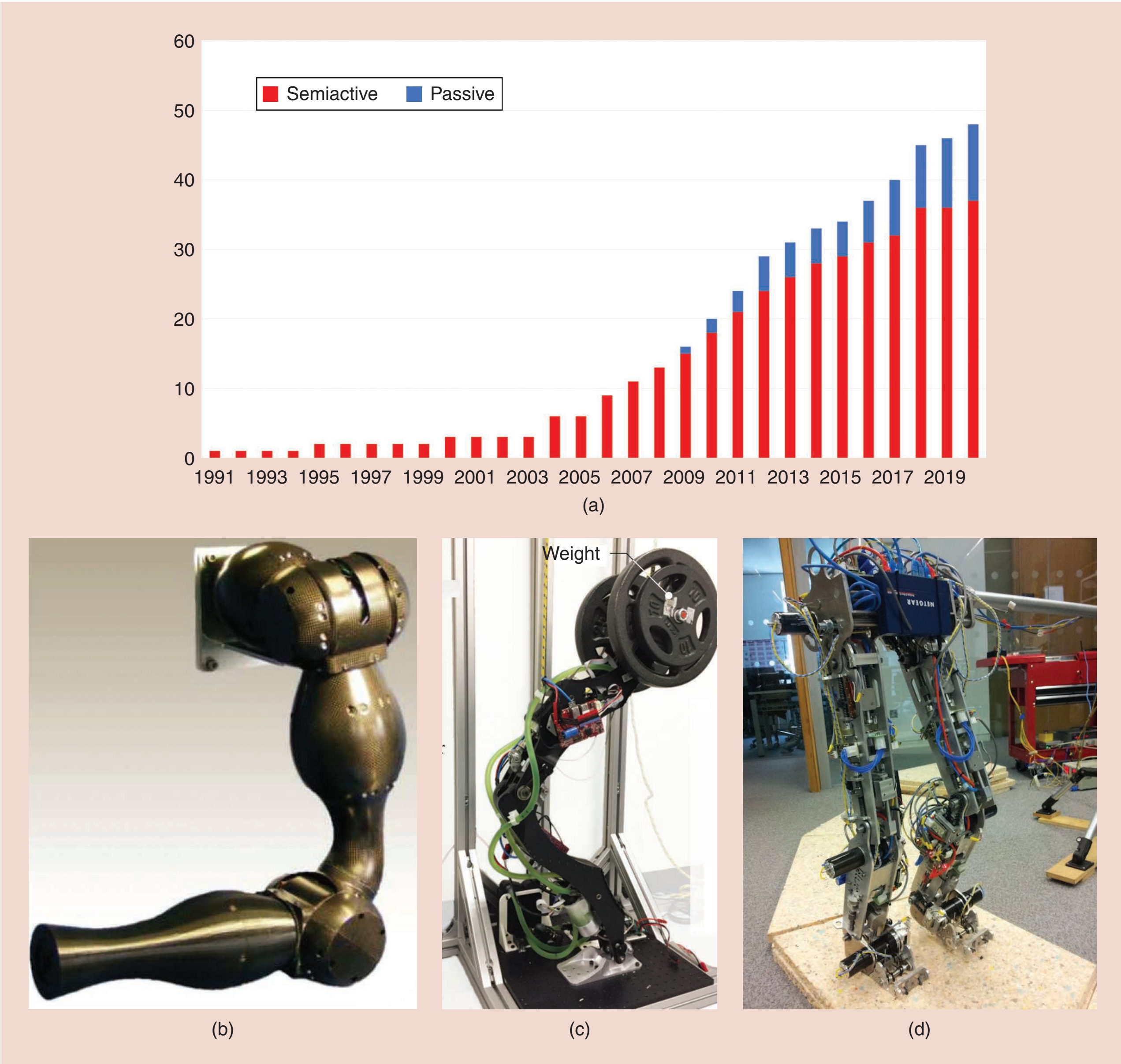


Figure 1. (a) The trend in the study of damping systems in the actuation of compliant robots. The bars are proportional to the number of published papers about damping in soft actuation. Information from the database (see the "Database Identification" section) has been cross-checked to count the papers according to their control (b) A compact Arm from [26] (license 5210131303438). (c) A viscoelastic liquid-cooled actuated leg testbed from [27] (license 5210131175828). (d) Blue, a bipedal robot with variable stiffness and damping from [6] (license 5210131223138).

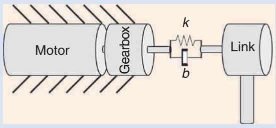
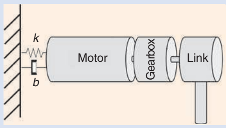
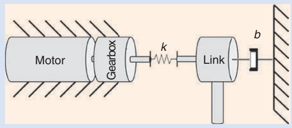
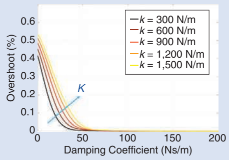
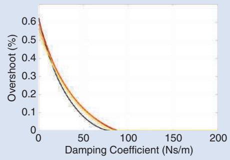
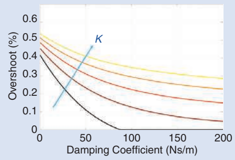
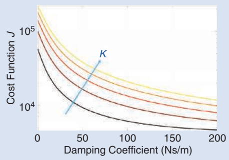
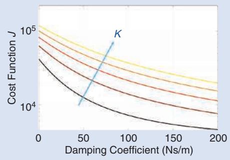
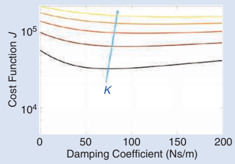
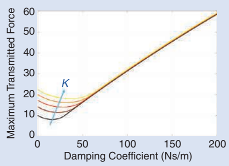
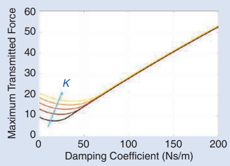
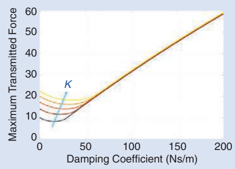
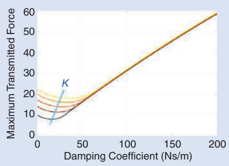
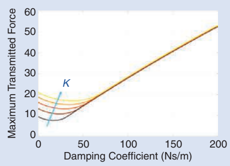
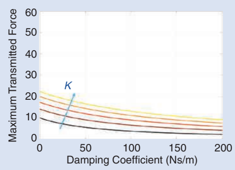
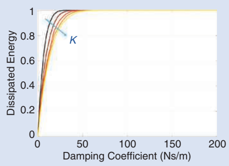
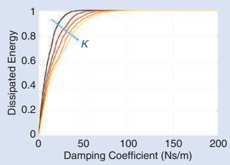
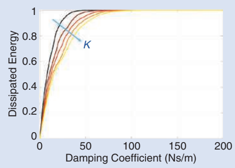
dependency of task performance to the amount of damping is in [37]. There, the authors study the effects of damping in a hopping leg and find an optimal tradeoff between three competing requirements: handling the shock of landing, enhancing leg energy storage, and mitigating oscillations to avoid undesired rebounds. Nevertheless, most applications define complex objective functions that depend on a combination of several costs similar to those reported in Table 1. Sometimes the objective function can be so complex and intertwined with other aspects of the system that it cannot be broken down into simpler costs. An example of this is the Z-width used to evaluate the quality of haptic devices [38], [39].

Although specialist literature shows that the range of impedance that some actuators can render increases with damping, the precise dependency of this relies on several other aspects, including the control law used to implement the haptic rendering, and it is not easy to study independently. Although the focus of this article is not stiffness, it is worth briefly mentioning how cost functions change with elasticity. In general, a greater stiffness increases the natural frequency and decreases the damping ratio. That results in faster oscillatory dynamics and a reduced shock absorption capability. To go deeper in this topic, we refer the reader to [40]. In conclusion, the sheer variety and many facets of the problems that arise when designing a damper for a soft robotic actuator promoted the exploration of the solutions we review in the following sections.

Database Identification

To paint a comprehensive picture of state-of-the-art damping elements in robotic actuators and joints, we covered the past 30 years of research through a meticulous search in the databases of Google Scholar, IEEE *Xplore*, and Sage Journals,

Table 1. The dependency of typical cost functions related to different tasks.

Objective	Cost Function	SEDA 	rSEDA 	SEAwEPD 
Task precision	The cost is estimated as the overshoot of the system during a step response: *OS*%.			
Control performance	The cost is evaluated as the linear quadratic regulator performance index function: $\int_0^\infty x^T Qx + u^T Ru\, dt$.			
Human safety	The cost evaluates the transmitted force at the link side during an impact: $F_{\text{transmitted}} = f(Kx, B\dot{x})$.			
Robot resilience	The cost is evaluated as the transmitted force at the gearbox side during an impact: $F_{\text{transmitted}} = f(Kx, B\dot{x})$.			
Energy storage	The cost is assessed as the percentage of the energy dissipated during task execution: $\frac{\Delta E_{\text{diss}_{\text{task}}}}{E_{\text{tot}}}$.			

The dependency relates to the damping coefficient for the main elastic damped actuation topologies found in literature (see the "Topology" section). We chose not to include legends in any figures except the first plot. Indeed, this legend applies to all of the graphs in the table.
SEDA: series elastic damped actuator; rSEDA: reverse SEDA; SEAwEPD: series elastic actuators with external parallel damping.

which collectively cover more than 8 million papers [41]. Our search strategy, based on the Prisma methodology [42], relied on the selection of the keywords reported in Table 2. Then, the outcome of this search (1,461 papers) was manually reviewed to exclude irrelevant works. Finally, we manually searched the bibliography of the remaining papers to identify and include other potentially relevant studies.

Our selection method is the one we think is the fairest and most unbiased. However, we are aware that it has some limits. For example, it does not consider the quality of the work, the impact factor, and the performance of each device. Our database has been updated to include advice provided by the reviewers. The final output of these three operations led to the identification of 52 works that collectively describe 44 devices. These publications were carefully reviewed and categorized based on their design and application domain, adopting the criteria described in the following sections. To make our results available to other scholars, we collected data from the reviewed papers into a database available at https://www.naturalmachinemotioninitiative.com/damping-in-compliant-actuation-a-review.

Active, Passive, and Semiactive Damping

Many applications require the damping ratio of a system to change on a case-dependent basis. Nevertheless, introducing possibly variable physical damping elements into a system increases costs in terms of weight, clearance, and resources. Approaches to solve this tradeoff led, through the years, to three families of solutions that differ based on their ability to change the exhibited damping ratio and how much attention the control system uses to do so. Following a classification inspired by the automotive world [25], [43] and already used in [44], it is possible to divide damping systems into three categories: active, passive, and semiactive. Figure 2(a) presents the distribution of passive and semiactive damping systems in the database.

Passive Damping Systems

A straightforward way to dampen oscillations is by relying solely on passive mechanical components, such as dashpots. Physically damped systems are energy-wise passive, a property that guarantees their intrinsic stability and makes designing robot control simpler. The cost for that is a moderate complication of the mechanical design. The main drawback is the impossibility of changing the implemented damping ratio, so performance depends on fitting the damping coefficient to the task specifications, which can be done only at design time (see the "Motivations" section). This limitation is the most likely motivation behind the fact that despite passive dampers having a long history [45], the robotics literature did not consider their inclusion in robots with soft actuators until late in the first decade of the 2000s, as Figure 1(a) testifies. An example of a passive system developed in that period is the viscoelastic joint for rehabilitative purposes described in [46].

Active Damping Systems

At the opposite end of this axis lie active damping systems. They prioritize the minimization of additional system components by relying on a software implementation of the damping action. They are usually based on the fine control of torque, which they have to measure through a sensor and by other means. Two extensive reviews of the use of active damping methods are [28] and [29], to which we direct the interested reader. We report only that although the software nature of active damping yields the best theoretical freedom in tuning dynamic parameters, in practice, active dissipation may be limited by instability phenomena due to the communication bandwidth, sampling time, and computational power [47].

Semiactive Damping Systems

Semiactive damping systems try to merge the task-wise versatility of active damping systems with the intrinsic stability of passive ones. To do so, they use physical damping components whose action can be regulated online. The cost of this is paid in terms of design complexity. Indeed, semiactive damping requires a variable mechanical damping component and an extra motor to operate it. In this, they are to passive dampers analogous to what variable stiffness actuators are to compliant

Table 2. The number of published papers found in different databases.

Keywords										
Damping	Robotics	Actuator	Physical	Passive	S.-Active	IEEE *Xplore*	Sage	Google Scholar	IEEE *Xplore*	Sage
X	X							203	1.664	1.523
X		X						161	1.987	7.372
X	X	X						34.8	323	1,039
X	X	X	X					29.3	51	684
X	X	X		X				21.8	15	306
X	X	X	X		X			3.08	3	174
X	X	X	X		X	X		1,020	—	159
X	X	X	X		X	X	X	979	—	—

S.-Active: semi-active.

actuators with fixed stiffness. Although semiactive damping requires some energy to operate the damping regulating motor, this prerequisite is lower than in the active case [48].

A significant number of papers from the past 30 years, and this review, deal with semiactive damping for soft robotic actuation. The reason for that is dual. On the one hand, semiactive damping systems feature higher versatility than passive ones, which is often fundamental for many applications. On the other hand, the design of a semiactive damping system is more complicated and requires newer solutions than those found in the state of the art. One of the first examples of semiactive dampers found in literature is [49], a robotic joint with a nonlinear programmable spring and binary programmable damper.

Damping Technology

The examination of the database led to the identification of seven physical principles as a source of nonconservative forces to engineer damping. We arranged these into four groups that are reported in Table 3. Figure 2(b) provides the distribution frequency of these technologies in the database. We observe that friction dampers and variable-rheology fluid dampers are used the most in the literature. The authors of [50] and [51] compare these technologies, concluding that friction dampers have greater applicability when environmental conditions vary on one side and that variable-rheology dampers offer finer damping control on the other side. Both papers expect future developments to combine the advantages of the two technologies. In the following, we briefly describe and comment on each of the identified technologies and their use in passive and semiactive damping systems.

Fluid Dynamics-Based Dampers

Fluid dynamic dampers rely on the parasitic forces that arise in a fluid flowing when the flow gradient is not null, a phenomenon that happens in the proximity of one or more surfaces. In general, it is difficult to find the distribution of these forces. The problem can be described by the well-known Navier–Stokes equations [52] and solved through simulations and specialized software. Nevertheless, a simple and powerful instrument to characterize the forces' ensemble behavior is the Reynolds number (*Re*) [53]. We can distinguish between laminar flux when the number is small ($Re < 2,500$) and turbulent flux when the number is large ($Re > 4,000$).

For our analysis, distinguishing between the two behaviors is important since in laminar flows the damping effect is linearly proportional to the flow speed [54], while in turbulent flows we can observe a quadratic behavior. These behaviors correlate to the subfamilies of fluid dynamic dampers, which are meatus dampers, where the flow is laminar and the damping is linear, and orifice dampers, where the flow is turbulent and the damping is quadratic. A main advantage is the wide spectrum of energy dissipation density led by the vast range of viscosity levels held by these fluids, making them suitable

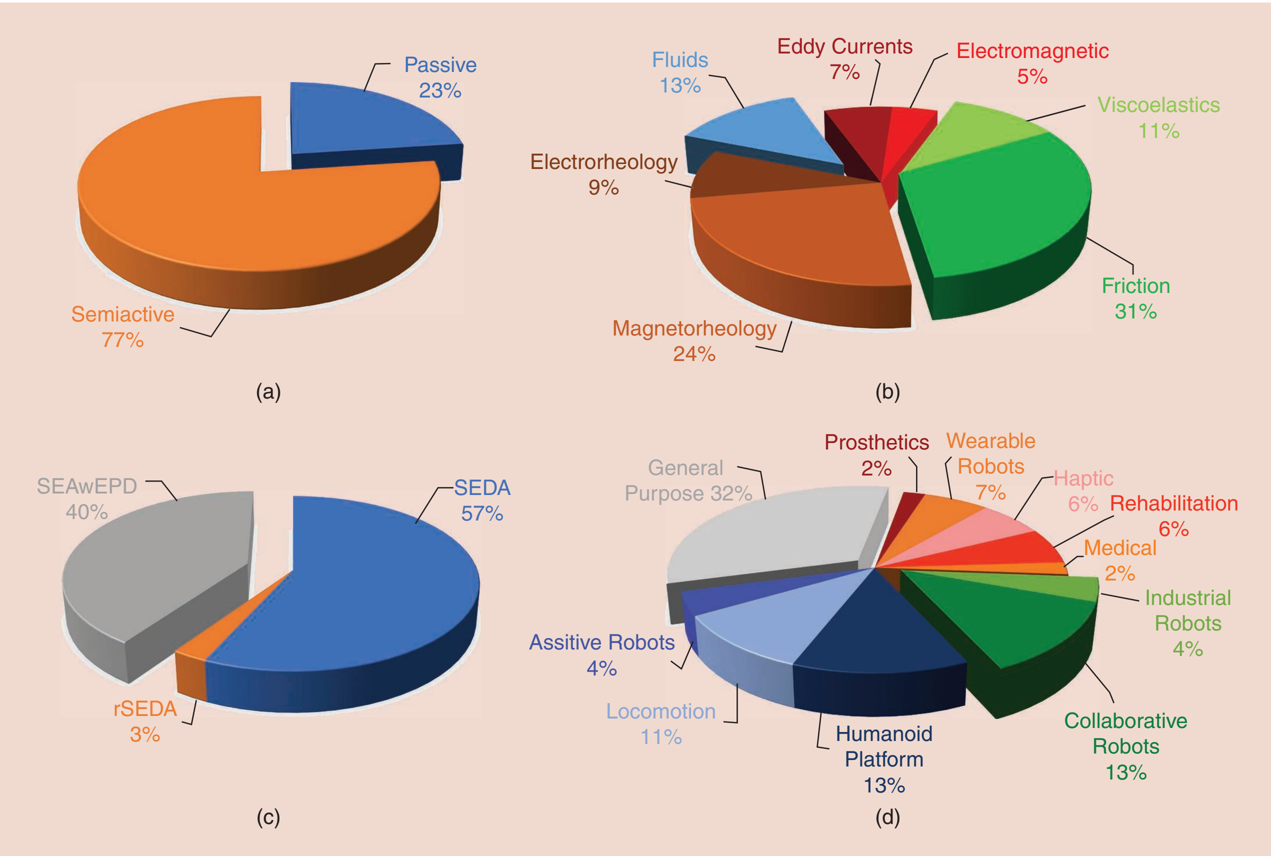


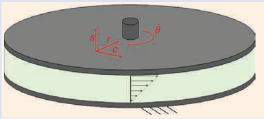
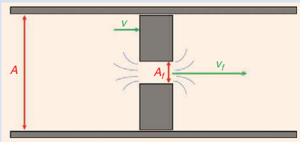
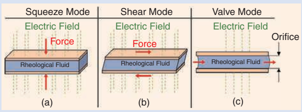
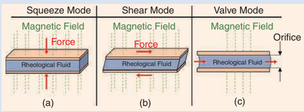
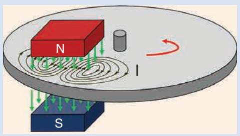
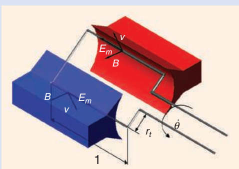
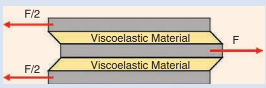
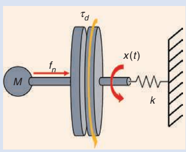
Figure 2. The use of (a) damping types, (b) technologies, (c) topologies, and (d) applications in the state of the art.

for compact, high-damping solutions. On the other hand, the slow dynamic of viscous fluids influences the damping regulation response. Additionally, fluids between moving elements require precise seals to avoid leaks.

Meatus Dampers

In these components, a viscous fluid lies between two plates in relative motion (Table 3, row 1). The viscous fluid opposes the relative motion between its layers, generating a linear damping action that is proportional to the speed of the motion. The system described in [55] offers an example of this technology. It is possible to design a meatus damping system to be semiactive: an architecture to achieve continuous semiactive damping could change the relative overlapping area of the moving plates [55]. Alternatively, by engaging and disengaging the motion of the plate(s) with the actuator organs, it is possible to vary the damping in discrete steps. The authors of [49] present a semiactive system with a fluid that passes between chambers

Table 3. A summary of the damping technologies found in the literature.

Group	Technology	Model	Equations	Notation
Fluid dynamic	Meatus dampers		$\tau = N\int_{r_1}^{r_2} 2\pi\mu\omega\frac{r^3}{t}dt,$ $\tau = N\frac{\mu\pi(r_2^4-r_1^4)}{2t}\omega.$	μ = dynamic viscosity r_1, r_2 = inner and outer radius of damper t = thickness of the meatus ω = angular velocity N = number of meati
	Orifice dampers		$\tau = \frac{\delta A}{2g}\left[\alpha_f\frac{A_f^2}{A^2}-\alpha\right] R^3\omega^2.$	A = fluid contact surface A_f = orifice section δ = fluid density g = gravity α_i = flow coefficient $_f$ = orifice-related values R = radial position of holes ω = angular velocity
Variable-rheology fluid	Electrorheological fluid dampers		$F_{ER} = 4\pi RL_d(\eta\dot{\gamma}/h + \alpha E^{\beta} sign(\dot{\gamma})).$	η = viscosity E = electric field h = electrode gap L_d = electrode length R = mean radius of the moving cylinder α, β = intrinsic values $\dot{\gamma}$ = relative pole velocity
	Magneto-Rheological fluid dampers		$F_{MR} = \eta A\dot{\gamma}/h + \tau_y(H)A.$	η = viscosity h = electrode gap H = magnetic field $\dot{\gamma}$ = relative pole velocity A = shear pole area
Electromagnetism	Eddy current dampers		$\tau = N\frac{wB^2S}{\rho L}R_a^2\dot{\theta}.$	N = number of plates ω = plate radius B = magnetic field S, L = section, length of equivalent wire ρ = electric resistivity R_a = mean radius
	Motor-like electromagnetic dampers		$\tau = N\frac{lh^2B^2\cos^2\theta}{2r_t}\dot{\theta}.$	l, h = coil dimensions N = coil number B = magnetic field r_t = mean radius $\dot{\theta}$ = angular velocity
Friction	Viscoelastic dampers		$\tau = K\theta + B\dot{\theta}.$	$\theta, \dot{\theta}$ = angular position and velocity K = elastic coefficient B = damping coefficient
	Braking effect dampers		$\tau = \begin{cases}\mu_d f_n, \dot{q} \neq 0 \\ \mu_s f_n, \dot{q} = 0\end{cases}.$	K = friction coefficient f_n = normal force to plates

through pipes with small diameters. Capillarity enables the system to achieve linear damping through a laminar flow.

Orifice Dampers

Orifice dampers are systems in which a fluid is forced to flow through a hole between two chambers. As evident in Table 3, row 2, they generate a damping action that is quadratically proportional to speed [56]. The devices described in [46], [49], [57], and [58] are examples of this technology. The first three use a silicone tube filled with a viscous fluid that is forced to move to achieve a damping effect. The fourth achieves variable damping by pushing a viscous fluid through a variable-diameter orifice operated by a motor, by all terms, a valve. Variable-orifice viscous dampers find wide use in other fields, particularly the automotive industry.

Variable-Rheology Fluid Dampers

These damping mechanisms rely on a particular class of fluids that vary their rheological behavior when subjected to a magnetic or an electric field. They can change from free-flowing viscous liquids to semisolids, with a yield strength that depends on the magnitude of the externally applied field (magnetic or electric) [59]. The natural application of electrorheological (ER) and MR fluids is in semiactive damping systems, where their intrinsically variable behavior finds its best use. Usually, ER and MR fluids consist of microscopic particles suspended in a carrier medium. These particles can be polarized electrically or magnetically (for ER and MR, respectively), so when an external electric or magnetic field is applied, they align along the field lines and act as a barrier to the flow of the carrier. An extension of the Bingham plastic model can describe the behavior of an ER or MR fluid subject to an electric or magnetic field, as shown in Table 3, row 3. Further information about ER and MR fluids and their applications can be found in [60]. Three approaches are possible to design a damping system based on variable-rheology fluids [61]: squeeze mode, shear mode, and valve mode.

Squeeze Mode Dampers

In squeeze mode dampers (Table 3, row 3) a volume contains the variable-rheology fluid that is squeezed away. An ER damper that uses squeeze mode is in [62], and an MR example is in [63].

Shear Mode Dampers

In shear mode dampers (Table 3, row 3), plates in relative motion are used to generate shear strain in the fluid. MR examples are in [64]–[69].

Valve Mode Dampers

Finally, in valve mode dampers (Table 3, row 3), the fluid is forced to flow through a narrow orifice, where the external field is applied. An ER damper that works in valve mode is reported in [61], and an MR version is in [70]. Rheology dampers have proved to be advantageous in terms of fast control response and simple mechanics since they do not require additional movers to vary their properties. They also present disadvantages. MR fluids tend to settle through time without frequent mixing. Particles are liable to stick together due to residual magnetization, making redispersion difficult and forming a hard layer [71]. ER fluids, on the other hand, have a tendency to chemically and mechanically react with diverse materials, necessitating precise damper component selection [72].

Electromagnetism-Based Dampers

This class of mechanisms relies on passive electromagnetic forces that resist the relative motion between a conductive object and magnetic field. They divide into two families. In the first, that of eddy current dampers (ECDs), the conductive body has a generic shape. In the second, motor-like electromagnetic dampers, the conductive body comes in the form of one or more wires that make a circuit. Electromagnetism-based dampers offer the advantage of avoiding friction, extending component longevity. Moreover, they have fast and precise dynamics. Their primary drawback is a low energy dissipation density [73].

ECDs

ECDs are passive electromagnetic devices composed of a conductive material moving through a magnetic field (Table 3, row 4). They exploit the Foucault currents induced inside a plate moving in a magnetic field. Examples of this technology can be seen in [74]–[77]. Permanent magnets and electromagnets can be used to realize ECDs. The most straightforward implementations use permanent magnets to produce passive damping [75]. Nevertheless, semiactive damping can rely on electromagnets as well as permanent magnets [74]. When using electromagnets, the electrically induced magnetic field controls the magnitude of the damping action. On the other hand, when using permanent magnets, it is possible to change the amount of damping by modifying the system geometry.

Motor-Like Electromagnetic Dampers

These systems exploit the same effect as those described previously but rely on a geometry that is similar to that of electric motors. In them, examples of which are in [6], [78], and [79], the conductive body forms a set of coils similar to a rotor, while a component comparable to a stator generates a magnetic field that can be constant if the component is built using permanent magnets or variable if the device uses other coils. Table 3, row 5, describes the physics [53] of a single coil rotating in the magnetic field. The many coils of the system are then short-circuited, possibly through a variable resistor, to generate a circulating current and back electromotive force, which induces damping. Passive damping can be obtained through permanent magnets on the stator [6], whereas it is possible to design semiactive damping by using electromagnets in the stator [78].

Friction-Based Dampers

This family of damping systems relies on forces that naturally resist the relative motion of solid surfaces. Such surfaces can belong to different contacting bodies as well as a single body that undergoes deformation. Friction arises from a complex combination of phenomena on a microscopic and molecular scale. These include adhesion, deformation, and contamination and depend on factors such as the roughness and composition of the involved material(s). The derivation of these forces from basic principles is not always practical. Nevertheless, tribology [80] and material sciences [81] yielded simpler approximated models that can be used for most engineering purposes. These models enable the design and study of the mechanical systems of robots and actuators. The two bottom rows of Table 3 report the most used of these models, which correspond to the two families into which we divide friction-based dampers: internal friction for viscoelastic dampers and Coulomb friction for braking effect dampers.

Viscoelastic Dampers

When a body deforms elastically and springs back to its original shape, not all the mechanical work applied to distort it is returned since part of it transforms in heat. These losses, which are more evident in materials such as rubber, tend to be proportional to the deformation speed and are described well by a viscoelastic model, including the one reported in the table. Examples of systems that use viscoelasticity for damping are in [5], [27], [82], [83], and [84]. An advantage of these systems is that they employ the same physical element to implement elasticity and dampening. Although this choice bounds the design of the two actions, imposing some constraint at design time, it reduces the number of mechanical parts and simplifies the architecture. The impossibility to decouple the elastic and damping effects, on the other hand, limits the application of this component. In the literature, all the examples that use viscoelastic components implement passive damping. This choice is probably motivated by the pursuit of simplicity. However, in principle, viscoelastic elements could be used to obtain semiactive damping by resorting to mechanical solutions similar to those to regulate stiffness in variable-stiffness actuators.

Braking Effect Dampers

When two surfaces are stacked and made to slide, they are subject to the phenomenon of dry friction, described by Coulomb friction equations, as reported in Table 3, row 8 [44]. Dry friction is used to design braking effect dampers. It is usually associated with brake systems since there is no direct correlation between the magnitude of the friction force and the sliding speed. Nevertheless, it can achieve other dissipating behaviors by modulating the normal force between the sliding surfaces. This aspect intrinsically forces braking effect dampers to be semiactive. Indeed, this is always the case in the examples found in literature: [26], [37], [44], [48], [85]–[91], and [92]. This approach complicates the design of braking effect dampers, which need an actuator to modulate the normal force. Different examples resort to various devices, from electric motors to hydraulic actuators and miniature piezoelectric actuators, motivated by application requirements. Nevertheless, the intrinsic necessity to modulate the passive force has the advantage of making braking effect dampers able to emulate any type of generalized damping effect if proper control is applied.

Finally, it is interesting to note that this kind of damper can produce high damping forces even at low velocities, a characteristic that is not common to the other families. The dynamics in these systems depend heavily on the type of actuator used to control the variable-damping action. The primary disadvantage, on the other hand, is the wear that pads endure when swiping each other. As a result, the pad location must be regulated to avoid compromising the control quality. Although we have not found examples in the literature, dry friction devices might operate as passive dampers. However, acting essentially as brakes, passive dry friction dampers would result in constant braking on the link. It is hard to find many cases in which that behavior would be beneficial.

Topology

As stated in the "Motivations" section, architecture topologies yield different damping system behaviors. The examination of the state of the art led to the classification of three topologies, which we report in Table 4, emphasizing the model and internal dynamics of each configuration. Please note that the explicit distinction between θ_m and θ_o is to highlight the possible oscillatory dynamics that could arise inside the actuation unit. Figure 2(c) details the distribution of these topologies in the database. We observe that the reverse series elastic damped actuator (rSEDA) has limited application in the literature. A possible reason for this, suggested by the study of shock transmission in actuation units [93], could be the superior suitability of SEDA and series elastic actuators with external parallel damping (SEAwEPD) in handling impacts, due to the interposition of elastic and damping components between the gearbox and link. In the following, we report and review the topologies in the database and discuss how other solutions could exist but were not found in the literature. We named each topology based on the relative position of the elastic and damping elements with respect to the motor, also considering the definition of the relative placement of these components made in [1].

The SEDA

The SEDA is the first and most used architecture topology found in the reviewed literature. This class of actuators is designed with elastic and damping elements interposed between the gearbox and output link [3], [12], as displayed in Table 4, row 1. An advantage of these systems is the reduced shock transmitted to the gearbox in case of impacts. Indeed, these components act like a filter, cutting off unexpected peaks of force. Moreover, during constant working conditions, this topology produces low dissipative actions. Conversely, the design of this system results in axial packing, increasing axial dimensions. This architecture topology is suitable to design semiactive and passive systems. Example passive devices are available in [6], [46], [82], [94], and [95], while semiactive systems are described in [48], [49], [58], [65], [67]–[70], [84], [88], [90], [91], [96]–[99], and [100].

The rSEDA

The rSEDA is a topology where a rigid actuator is connected to the frame by damping and elastic elements (see Table 4, row 2), and it features a dynamic behavior that is not very different than that of SEDA systems. Hence, this topology has similarly low energy dissipation during constant working conditions. We found it in only one work: [27]; therefore, it is not easy to draw general conclusions about its advantages and disadvantages. Nevertheless, one advantage seems to be reduced axial dimensions with respect to the other solutions. Conversely, a probable disadvantage is the fact that when it the system is subjected to disturbances and impacts, the whole actuation unit oscillates to absorb the force. Consequently, in the case of impulsive shocks, the force is transmitted to the elastic and damping components through the rigid actuator, resulting in a lesser degree of protection for the system than with the other topologies. Finally, although [27] opts for a passive design of the damping component, no ostensible impediments seem to prevent semiactive solutions.

The SEAwEPD

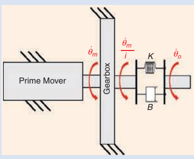
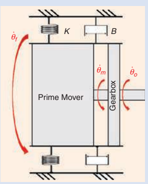
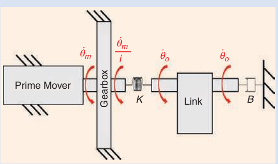
The SEAwEPD topology is the only one to feature a damper and spring that are not placed in parallel. Indeed, as illustrated in Table 4, row 3, the spring lies between the gearbox and link, while the damping acts between the link and the frame. This topology has attracted growing interest in research applications during the past decade (see the "Discussion" section). One of the clearest advantages of SEAwEPD topology is the greater resilience to shocks. This is because the damper relieves part of the stress directly to the frame (see Table 1, row 4). Similar to the SEDA, this topology tends to possess large axial dimensions, requiring an accurate design for integration. Moreover, due to the location of the damper, some dissipation is always present when the link moves, hindering the energy efficiency of motions. To fight this, the SEAwEPD necessitates a damper that can be disengaged when not in use. Therefore, the SEAwEPD is usually designed to be semiactive. Examples of devices designed with it are [5], [26], [44], [55], [61], [63], [64], [79], [86], [87], [89], [92], [101], and [102].

Applications

Through the years, research in the literature experimented with the application of damping systems across different fields of robotics applications. Through direct inspection of the documents in the database, we identified 10 application categories to which the works belonged. The categories, also reported in Figure 2(d), are assistive robots, collaborative robots, haptic systems, humanoid platforms, industrial robots, locomotion systems, medical devices, rehabilitative systems, robotic prostheses, and wearable robots. These cover roughly 66% of the papers; the remaining 33% did not note a specific field of application, and they were classified as "general purpose." The distribution of the 52 works that constitute the database across the 10-plus-one categories is sparse and irregular, making the issue of finding potential correlation trends with the other categories problematic. This difficulty is worsened by the intrinsic fuzziness that often accompanies the definition of a robotic application field. Hence, to face both these problems, we looked for macro classes that grouped several applications.

The macro categories are MHW robots, including robotic prostheses, wearable robots, rehabilitative systems, medical

Table 4. A summary of the damping topologies found in the literature.

Topology	Model	Equations	Notation
SEDA		$\begin{cases} i^2\tau_m = (J_m i^2 + J_r)\ddot{\theta}_m + B(\dot{\theta}_m - i\dot{\theta}_o) + K(\theta_m - i\theta_o) \\ \tau_{ext} = J_L\ddot{\theta}_o + B(\dot{\theta}_o - \dot{\theta}_m/i) + K(\theta_o - \theta_m/i) \end{cases}.$	J_m = motor inertia J_r = equivalent gearbox inertia at the output J_L = output link inertia τ_m = motor torque τ_{ext} = output torque B = damping coefficient
rSEDA		$\tau_{ext} = i\tau_m - (iJ_m - J_f/i)\ddot{\theta}_m - (J_r + J_L + J_f)\ddot{\theta}_o - B(\dot{\theta}_o - \dot{\theta}_m/i) + K(\theta_o - \theta_m/i).$	K = elastic coefficient θ_m = motor angular position θ_o = output angular position i = gearbox ratio J_f = elastic and damping component inertia
SEAwEPD		$\begin{cases} i\tau_m = (J_r/i + J_m i)\ddot{\theta}_m + K(\theta_o - \theta_m/i) \\ \tau_{ext} = K(\theta_m/i - \theta_o) - B\dot{\theta}_o - J_L\ddot{\theta}_o \end{cases}.$	

devices, and haptic systems; ICRs; and HAL systems, consisting of humanoid platforms, systems for locomotion, and assistive robots. These macro categories will be of fundamental importance in the "Discussion" section to study the correlation trends with the aspects that we introduced in the "Active, Passive, and Semiactive Damping," "Damping Technology," and "Topology" sections. To identify the macro classes, we resorted to analyzing semantic data mined from the Sage database. In particular, using the application categories as search keywords, we estimated the likelihood that each pair of applications appears together in the same publication. This was estimated as the ratio between the frequency with which both keywords appear together over the frequency with which either of the two appears. Using the Shannon entropy associated with those probabilities as a dissimilarity matrix, we constructed the agglomerate hierarchical cluster tree (the authors of [103] implemented this with the MATLAB linkage function). Setting a dissimilarity threshold of 2.5 on the Shannon entropy groups the 10 application categories into the three macro categories.

Figure 2(d) presents the distribution of the database entries among general-purpose systems and those that are designed with a specific application in mind. The application categories are grouped into the three macro categories. We observe that the most common applications are humanoid robots, collaborative robots, and locomotion systems. The final one is surprising at first since one of its most important performance indicators is energy efficiency. Nevertheless, as explained in the "Motivations" section, if the action is low, damping can be used to filter oscillations, another important goal of locomotion systems, with limited energy loss. In the following, we briefly describe each application category and comment on the use of damped robotic actuation. The applications are grouped into the macro categories described previously.

MHW Robots

Medical Devices

Many robots have medical applications to aid patients and caregivers, improve the quality of service, and lower costs. This category includes, for example, devices for diagnostic purposes and to perform surgery. In it, we find [61], whose authors propose a device that returns force feedback from a patient during a magnetic resonance imaging (MRI) exam, where damped compliant actuation renders and reproduces forces to the patient. An example of a surgical robot is in [104], which describes the benefits of having active and semiactive damping technologies for remote surgery. At this level of granularity, this category does not include prosthetics and rehabilitation robots, which are considered separately in the following.

Robotic Prostheses

Prosthetic robots are meant to substitute for lost limbs and restore functionality. Depending on the part that is being replaced, robotic prostheses tend to rely on rigid as well as compliant actuation systems. Lower-limb prosthetic systems depend on compliant actuation, and among them, the use of damping systems reached some diffusion. Indeed, the authors of [67] present the control and design of an MR prosthetic knee that exploits an actuation unit in parallel with clutches to enhance the human-likeness of the movement of the joint. Finally, the authors of [98] introduce an ankle/foot system in which a certain degree of damping action is added to the elasticity to enhance safety and natural behavior.

Rehabilitative Systems

Rehabilitative robots help people reacquire abilities they lost because of injuries and illnesses, such as strokes [105]. A rehabilitation robot can act as a substitute by offering a lost capacity to a patient and as a therapy tool by assisting a patient relearning a function. Several robots in this category use damped compliant actuation. In [69], the authors present devices for upper-limb rehabilitation, such as Exercise Machine for Upper Limbs (EMUL), Robotherapist, and PLEMO. EMUL is a 3D device that can display sensed force in tridimensional spaces. Robotherapist is a six-degree-of-freedom (6-DoF) force display system, including wrists, while PLEMO is a haptic device capable of rendering virtual forces as output. All the devices employ ER actuators. Finally, in [84], the author designed a series of viscous actuators exploiting viscoelastic materials, which are implemented in a rehabilitative device, enhancing safety during interactions. Therapeutic aids and assistive devices may come in the form of exoskeletons and exosuits; see, e.g., [46] and [57]. Consequently, the boundary between rehabilitation and wearable devices is sometimes fuzzy.

Wearable Robots

These robots are worn on the body of a user. Most notably, this category includes exoskeletons, which support and assist with tasks. Different typologies exist, from power augmentation systems (i.e., [106]) and support devices for impaired people to rehabilitation aids. Several exoskeletons use damped compliant actuation systems in their design. In [46] and [57], a wearable device with an elastic damped joint is designed for knee rehabilitation and movement assistance [Figure 3(e)]. In [91], a wearable device capable of dynamically regulating impedance is introduced. However, exoskeletons are not the only example of wearable systems. The authors of [100] present a supernumerary leg in which an MR damping system is added in the actuation unit, enhancing the stability of the system even in the presence of high controller gains. In [82], the authors present an elastic damped device that can be utilized in the joints of a wearable system to measure torque and smooth movements during human–robot interaction.

Haptic Systems

Haptic systems render the sense of touch while interacting with a virtual environment. This category naturally overlaps the previous one since several wearable devices are designed as haptic renderers (e.g., [107]). Another partial overlap exists with the category of medical robots; the reported example in [61] integrates haptics into an MRI scan. Nevertheless, the field of haptics is more general, both in terms of design and purpose, and constitutes a multifaceted subfield of robotics. The authors of [38] study the effects of passive impedance in haptic feedback. Figure 3(d) shows a friction damper elastic actuator from [86] that is designed to be more capable of rendering hard contacts. Finally, in [76] and [77], the authors present ECDs to render haptic interfaces with virtual environments.

ICRs

Industrial Robots

Industrial robots are employed to automate repetitive activities. They constitute one of the oldest applications of robotics itself. Despite their maturity, they are adapted to perform more tasks with better performance. Thus, physical impedance may need to be added to their structures. In [64] and [96], the authors present, respectively, an actuator for

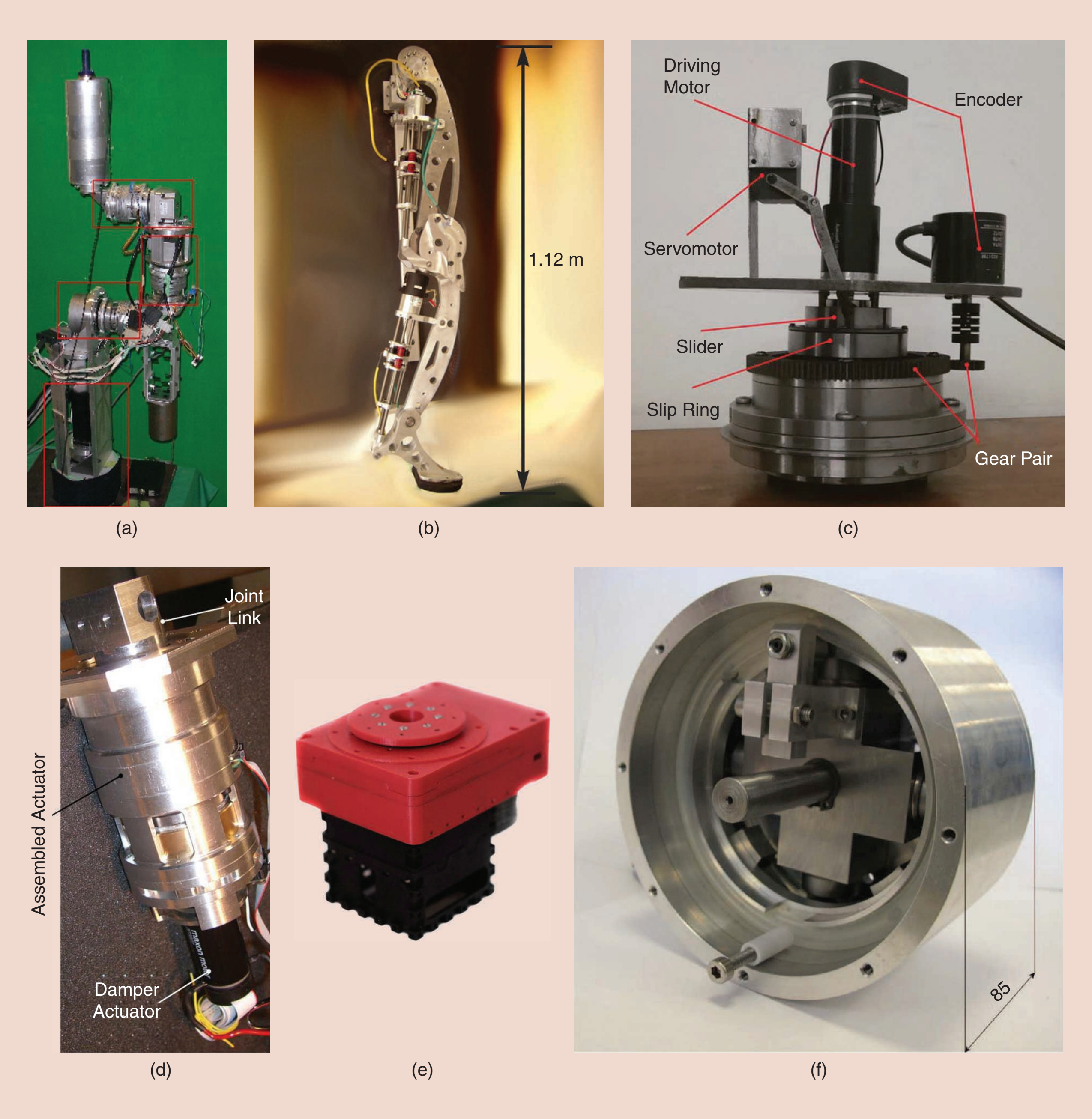


Figure 3. Systems featuring physical damping action. (a) A 4-DoF arm with series clutch actuators from [90] (license 5210140232588). (b) A prototype of the hybrid actuator development leg, which has series elastic actuation with an MR damper for agile locomotion, from [70] (license 5210131341002). (c) A prototype of a variable-damping actuator for compliant joints from [58] (license 5210140332587). (d) A friction damper elastic actuator for haptic applications from [86] (license 5210140291361). (e) A variable-damping system for a variable-stiffness actuator cube [55] (license 5210131081622). (f) The passive viscoelastic joint: a passive elastic damped joint for a wearable knee exoskeleton from [46] (license 5210191378602).

industrial robots with ER dampers and a robotic joint with a mechanical impedance adjuster for grasping. In these, damping components are inserted to enhance precision, while the possibility of unknown objects in the working space of the robots requires a certain degree of resilience.

Collaborative Robots

A category of robots derived from the previous one while importing several advances from robotic research is that of collaborative robots, i.e., those that work while interacting with humans in a shared space. Although their first application was in industry, they are moving to several other sectors since they guarantee human safety [108]. This assurance is often thanks to the inclusion of nontraditional actuation systems. For instance, the authors of [26], [44], and [48] present a damping system design for an actuator used to build a 4-DoF arm with bioinspired elastic and damped behavior [Figure 1(b)]. In [90], the authors present a 4-DoF manipulator that employs clutches to limit the maximum torque to a safe level [Figure 3(a)]. In [99], an MR actuator is designed to enable safe interaction between humans and robots.

HAL Robots

Humanoid Platforms

Humanoid platforms include robots that resemble people and carry out tasks with a level of performance comparable with that of humans. Recently, to increase the robots' "human-likeness," research has focused on design aspects concerning actuation and resilience. In [55], the authors present a variable-damping system for modular robotic actuators [Figure 3(e)]. These actuators can be connected to create different structures. Viscoelastic actuators have also been used to create a bipedal system, such as [5], that exploits a viscoelastic liquid-cooled actuator. In [58], the authors propose a variable-damping actuator for compliant joints [Figure 3(c)]. In [85], the authors introduce an actuator with controllable friction damping. This category blends naturally with the next one since most humanoid robots rely on legged locomotion.

Legged Systems for Locomotion

Legged platforms draw inspiration from natural systems to be able to walk, run, and hop. In their development, compliance and damping are used to optimize energy efficiency and smooth movements to replicate natural behavior. Damping provides other advantages. Indeed, the authors of [109] show how it is possible to reduce the required control energy and peak power consumption. Moreover, in [6], the authors describe Blue, a bipedal walking robot with variable stiffness and damping to enhance robustness against disturbances and impacts [Figure 1(d)]. In [98], the authors present an artificial ankle system capable of providing biologically realistic, dynamic behaviors; it exploits passive compliance and a variable-damping element. Also, for hopping robots, in [7] the authors present a compliant variable-stiffness leg with damping control, while in [70] and [27] they introduce, respectively, the Hybrid Actuator Development leg for agile locomotion [Figure 3(b)], made by exploiting series elastic actuation with an MR damping component, and a viscoelastic liquid-cooled actuator [Figure 1(c)].

The work in [37] introduces a leg that exploits damping to smooth the force reaction on the ground during a jump, comparing the efficiency of a friction damper with a compliant system and a hydraulic one. Finally, there are legged robotic systems capable of walking, running, and hopping. In [95], the authors present a viscoelastic bipedal robot and its trajectory generation strategy, while the authors of [110] introduce two examples in which the same task is it is performed using only compliance. The authors of [79] describe a variable-damping module for walking application, used for energy regeneration.

Assistive Robots

Assistive robots perform physical tasks for people with disabilities and senior citizens. Although the name might suggest similarity to the first macro category, our analysis describes a different reality. *Assistive robotics* is a term used mostly by researchers close to the field of locomotion systems. In [66], the authors present an MR fluid clutch for human-friendly actuators. The authors of [102] introduce another MR damper for high-performance physical human–robot interaction. These works present actuators for assistive robot but without implementations. Nevertheless, the work to design actuation units for this purpose is valuable, and we think it is worthwhile to present it. The lack of implementation is, in our opinion, related to the fact that, even if assistive robotics is a vast field, it has a low technology readiness level, with applications that are speculative and in development.

Discussion

Trend Analysis

While Figure 1(a) gives the speed with which the interest in using dampers in robotic actuation arose in the early 1990s, Figure 2 breaks down the development trends, from the viewpoint of each categorization described in the previous sections. Figure 4(a) illustrates how a large part of the research effort has always been dedicated to semiactive damping systems. Nevertheless, since the late 2000s, we observe the birth of a small but consistent degree of interest in completely passive damping systems. In our interpretation, the main motivation of the early and dominant interest in semiactive systems is that the possibility of modifying damping action makes robots able to work in different conditions (see the "Motivations" section). The recent interest in passive damping systems is due to the pursuit of simplicity, a topic that has become increasingly prominent in modern robotics [111]. Indeed, when the boundaries of an application are narrowly defined, simpler design and control can be preferable over tunability to favor usability, robustness, and economy.

Figure 4(b) describes the trends in the adoption of different damping technologies. Note how a substantial amount of research effort is always devoted to fluid dampers with fixed and variable rheology. Between the two, variable rheology has the lion's share, an aspect that partially correlates [also see Figure 5(b)] with their intrinsically controllable nature and the predilection for semiactive solutions observed in Figure 4(a). Indeed, in the design of semiactive systems, variable-rheology dampers are easy to control in the absence of additional movers. Papers about electromagnetic dampers are scarce and concentrated between 2006 and 2013. We suspect that their poor success could be explained by the observation that the size and mass of an electromagnetic device that should dampen a torque at a given speed closely resembles the size and weight of the electric motor used to move the actuator in the first place. This makes it more difficult to find applications where performing dampening with active solutions on the motor side is not more convenient. Finally, from 2010 to the present, we observe a substantial shift toward friction-based dampers. Once again, we presume that their simplicity and lack of fluids (and seals and leaks), together with their effectiveness, motivates this approach now that the technology is nearing real applications.

Figure 4(c) compares the effort devoted to developing different topologies through the years. As anticipated in the "Topology" section, the SEDA architecture is the oldest and most investigated in the referenced papers. A possible reason for this could be the topology's reproduction of the traditional mass–spring–damper conceptual architecture, which the SEAwEPD began altering to offer a different dynamic characteristic (recall Table 4) that may be more suitable for some applications. Nevertheless, one thing keeping the SEDA in use is its suitability to passive and semiactive solutions, whereas the SEAwEPD is almost always employed in semiactive scenarios. Finally, note that the rSEDA topology appeared recently in the literature, and only a few works about it exist. Although we acknowledge its originality, which made it worthy of being included in this article, it is difficult to locate trends and correlations between it and other categories, due to its novelty. Therefore, in Figure 5(a) and (b), we grouped rSEDA and SEDA configurations, as they share many properties.

Figure 4(d) examines how damping systems for robotic actuation are spread across the fields presented in the "Applications" section. We observe that a substantial number of the earliest works (all until 1997, most until 2005) do not focus on one application but remain general purpose, a trend that is pretty natural for the earliest development stages of a technology characterized by a low readiness level [112]. To confirm

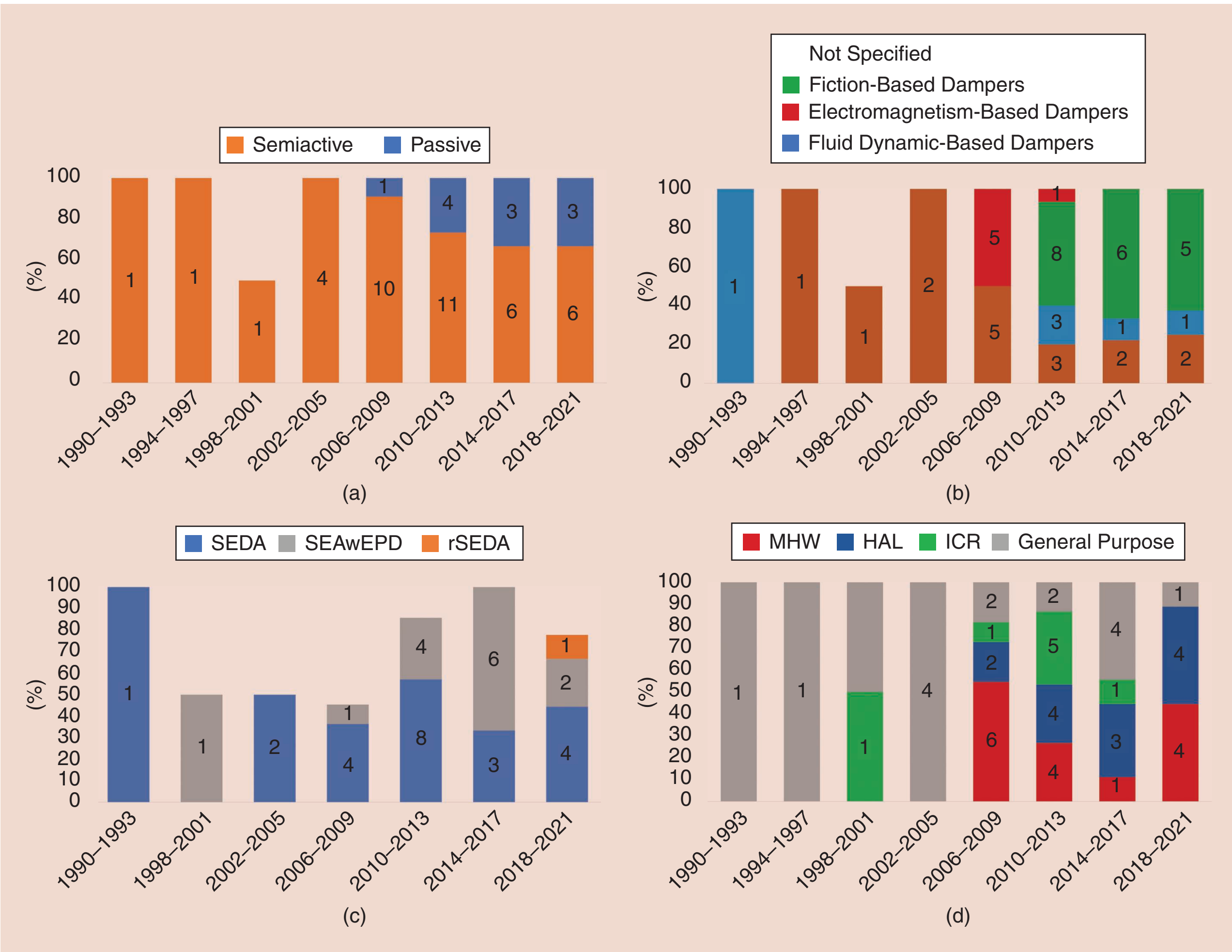


Figure 4. The trends for (a) damping types, (b) technologies, (c) topologies, and (d) applications.

Figure 5. The interconnections among categories in the referenced works. Each subfigure shows the correlation between the (a) damping type and topology, (b) damping type and technology, (c) technology and topology, (e) damping type and application, (f) topology and application, and (g) technology and application. In (d), we report the legend for the colors in (b) and (c), and in (h), we provide the legend for the colors in (e), (f), and (g).

this, we note how most application-oriented developments began becoming predominant around 2006, suggesting an increase in the technology readiness level. A significant exception to the 2006 application boom comes from the field of ICRs, which bloomed as early as 2000. We believe that this resulted from the closeness of robotics to industrial applications on one side and the concurrent development of the technologies that led to modern collaborative robotics around those years [113] on the other. Finally, the recent predominance of MHW and HAL application fields is most likely connected to the growing general interest in human–robot interaction, medical robotics, exoskeletons, humanoids, and legged locomotion systems [114].

Analysis of Design Interconnections

As discussed in the "Active, Passive, and Semiactive Damping," "Damping Technology," and "Topology" sections, the type, technology, and topology determine the main DoF in the design of a damped compliant actuation unit. Design choices about these three axes are, in general, correlated. Analyzing the literature to understand how and why these choices relate and how, in turn, they apply to different application domains provides useful knowledge about where the field has been and where it has not. Moreover, the revelation that unexplored categories could exist suggests a possible perspective on the future of this field. Indeed, by analyzing the distribution of damping architectures across the categories of semiactive and passive types, in Figure 5(a), we notice how few SEAwEPD systems have been designed with purely passive architectures. We believe that the most likely explanation is that in SEAwEPD actuators, the prime mover has to fight the damper all the time. Therefore, a passive system, which cannot be regulated, risks either dissipating too much energy or being insufficient.

In Figure 5(b), we observe that semiactive dampers are more frequently used in friction-based systems. Nevertheless, if we separate the contributions of dry friction and viscous friction systems, we recognize that most dry friction dampers are semiactive and all viscous friction dampers are passive. This probably stems from the fact that viscous friction effects are usually generated by the same physical element that introduces compliance into the system. It seems that, in all such systems presented so far, the elastic component and associated damper were not controllable. The possibility of regulating the damping in such architectures, e.g., with the same kind of mechanism that a variable-stiffness actuator system would use [1], remains unexplored. Variable rheology shows the opposite trend, where it is always used in semiactive systems, the motivation being the intrinsically variable nature of ER and MR systems.

Figure 5(c) emphasizes how the various technologies are employed among the topologies. The highlight is how SEAwEPD systems almost always rely on dry friction and variable rheology and less often on fluid dynamics and viscoelastic friction, while combinations with electromagnetic technologies have never been explored. We believe that this choice is motivated by the fact that SEAwEPD topology requires reducing the damping action in nominal working conditions, and dry friction and variable rheology are the most suitable for being regulated. Other interesting insights come from the next three subfigures, which correlate the architectural categories with their diffusion in the various applications.

Figure 5(e) analyzes the distribution of semiactive and passive damping systems across the various application families. Where the semiactive approach finds ubiquitous application, we see that passive systems were never studied in ICRs. This can mark a possible innovation opportunity, and it could suggest that passive damping systems poorly fit ICR applications. By analyzing the single applications within the categories, we notice how passive systems are widely used in locomotion and wearable robots, with passive architectures appearing in 60 and 75% of the papers, respectively. In locomotion systems, this diffusion is probably motivated by the narrow range of damping ratios that do not hinder energy storage, whereas passive dampers are more suitable for wearable robots because their simplicity leads to lighter systems that can be borne more easily. Finally, by observing general-purpose systems, we observe that the dominance of semiactive solutions is more pronounced than on average. We believe that, in this case, the relative absence of application-driven constraints favors more experimental designs.

Figure 5(f) shows the application-wise distribution of the SEDA (together with the only rSEDA) and SEAwEPD architectures. We observe a noticeable deviation from the average distribution in the ICR group, where the SEAwEPD is preferred over the SEDA, which is the favored topology everywhere else. To explain this, remember that all ICR systems opt for semiactive systems [also see Figure 5(e)]. In light of this, the SEAwEPD topology can offer the possibility of using the damping system to replace (or reduce the effort of) the locking system that back-drivable ICR arms must use [115], [116] when not in operation. Moreover, we find a large deviation from the average distribution in the class of MHW applications, where several more solutions rely on the SEDA rather than the SEAwEPD. In part, this is related to the heavy use of passive dampers within this class of applications. Another possible motivation for this could lie in the fact that having the damping in parallel to the spring, as in SEDA systems, leads to a mechanical output characteristic resembling that of musculoskeletal systems [117], a property that is welcome in MHW applications, especially in systems such as exoskeletons. Nevertheless, we cannot exclude the fact that this could be an under-investigated niche.

Finally, Figure 5(g) crosses the distribution of applications and technologies. In this analysis, we emphasize how ICR systems use either friction-based or variable-rheology dampers. This is most likely a consequence of the fact that such technologies are mainly employed in semiactive devices [Figure 5(a)] and that all ICR systems have semiactive damping [Figure 5(e)], the motivation being that ICR applications require precision and adaptability, depending on the operation phase. Two other minor deviations from the average behavior can be observed in the slightly larger number of fluid dynamic solutions used in HAL systems and the higher number of electromagnetic solutions explored for the development of general-purpose systems.

Conclusion

The introduction of damping in compliant robotic actuation promises highly dynamic, oscillation-free moving systems that will optimize energy consumption, withstand external disturbances, and approach natural likeness. This paper reviewed the robotics literature of the past three decades to trace the evolution of this technology. We collected our findings in a database of 49 papers that we analyzed from four points of view that we believe could be interesting to students and engineers in the field. We looked at the problem in terms of three technical elements that influence the behavior and performance of damped soft robotic actuators: whether they are passive or semiactive, the internal topology, and the technology used to implement the dampening. We considered the application fields for which these devices were developed, reviewing specifications and requirements. We reported the main classes that were observed from each of these points of view, describing their main functioning. Finally, we analyzed the distribution of the database entries within these categories, their trends through time, and their mutual distribution to highlight trends and underexplored options that we hope will guide the practitioner and inspire the scholar.

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References

[1] B. Vanderborght *et al.*, "Variable impedance actuators: A review," *Robot. Autonom. Syst.*, vol. 61, no. 12, pp. 1601–1614, 2013, doi: 10.1016/j.robot.2013.06.009.

[2] R. Van Ham, T. G. Sugar, B. Vanderborght, K. W. Hollander, and D. Lefeber, "Compliant actuator designs," *IEEE Robot. Automat. Mag.*, vol. 16, no. 3, pp. 81–94, 2009, doi: 10.1109/MRA.2009.933629.

[3] G. A. Pratt and M. M. Williamson, "Series elastic actuators," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. Human Robot Interact. Cooperative Robots*, 1995, vol. 1, pp. 399–406, doi: 10.1109/IROS.1995.525827.

[4] A. De Santis, B. Siciliano, A. De Luca, and A. Bicchi, "An atlas of physical human–robot interaction," *Mechanism Mach. Theory*, vol. 43, no. 3, pp. 253–270, 2008, doi: 10.1016/j.mechmachtheory.2007.03.003.

[5] J. Ahn, D. Kim, S. Bang, N. Paine, and L. Sentis, "Control of a high performance bipedal robot using viscoelastic liquid cooled actuators," 2019, arXiv:1906.03811.

[6] A. Enoch, A. Sutas, S. Nakaoka, and S. Vijayakumar, "Blue: A bipedal robot with variable stiffness and damping," in *Proc. 12th IEEE-RAS Int. Conf. Humanoid Robots (Humanoids 2012)*, 2012, pp. 487–494, doi: 10.1109/HUMANOIDS.2012.6651564.

[7] N. G. Tsagarakis, S. Morfey, H. Dallali, G. A. Medrano-Cerda, and D. G. Caldwell, "An asymmetric compliant antagonistic joint design for high performance mobility," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2013, pp. 5512–5517, doi: 10.1109/IROS.2013.6697155.

[8] A. J. Ijspeert, "Biorobotics: Using robots to emulate and investigate agile locomotion," *Science*, vol. 346, no. 6206, pp. 196–203, 2014, doi: 10.1126/science.1254486.

[9] M. Hutter *et al.*, "ANYmal—A highly mobile and dynamic quadrupedal robot," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, 2016, pp. 38–44, doi: 10.1109/IROS.2016.7758092.

[10] D. J. Blackman, J. V. Nicholson, C. Ordonez, B. D. Miller, and J. E. Clark, "Gait development on minitaur, a direct drive quadrupedal robot," *Unmanned Syst. Technol. XVIII*, vol. 9837, p. 98370I, 2016, doi: 10.1117/12.2231105.

[11] F. Petit, C. Ott, and A. Albu-Schäffer, "A model-free approach to vibration suppression for intrinsically elastic robots," in *Proc. IEEE Int. Conf. Robot. Automat. (ICRA)*, 2014, pp. 2176–2182, doi: 10.1109/ICRA.2014.6907159.

[12] J. Hurst, A. Rizzi, and D. Hobbelen, "Series elastic actuation: Potential and pitfalls," in *Proc. Int. Conf. Climbing Walking Robots*, 2004.

[13] M. Laffranchi, L. Chen, N. G. Tsagarakis, and D. G. Caldwell, "The role of physical damping in compliant actuation systems," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2012, pp. 3079–3085, doi: 10.1109/IROS.2012.6385883.

[14] G. Gasparri *et al.*, "Variable stiffness control for oscillation damping," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, 2015, pp. 6543–6550, doi: 10.1109/IROS.2015.7354312.

[15] W. Bernzen, "Active vibration control of flexible robots using virtual spring-damper systems," *J. Intell. Robot. Syst.*, vol. 24, no. 1, pp. 69–88, 1999, doi: 10.1023/A:1008035116904.

[16] T. Verstraten, P. Beckerle, R. Furnémont, G. Mathijssen, B. Vanderborght, and D. Lefeber, "Series and parallel elastic actuation: Impact of natural dynamics on power and energy consumption," *Mechanism Mach. Theory*, vol. 102, pp. 232–246, 2016, doi: 10.1016/j.mechmachtheory.2016.04.004.

[17] B. Vanderborght, S. Wolf, and G. Grioli, *Variable Impedance Actuators*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2020, pp. 1–8.

[18] L.-Q. Zhang, G. Nuber, J. Butler, M. Bowen, and W. Z. Rymer, "In vivo human knee joint dynamic properties as functions of muscle contraction and joint position," *J. Biomechan.*, vol. 31, no. 1, pp. 71–76, 1997, doi: 10.1016/S0021-9290(97)00106-1.

[19] K. P. Tee, E. Burdet, C.-M. Chew, and T. E. Milner, "A model of force and impedance in human arm movements," *Biol. Cybern.*, vol. 90, no. 5, pp. 368–375, 2004, doi: 10.1007/s00422-004-0484-4.

[20] I. D. Loram and M. Lakie, "Direct measurement of human ankle stiffness during quiet standing: The intrinsic mechanical stiffness is insufficient for stability," *J. Physiol.*, vol. 545, no. 3, pp. 1041–1053, 2002, doi: 10.1113/jphysiol.2002.025049.

[21] B. K. Ahlborn, R. W. Blake, and W. M. Megill, "Frequency tuning in animal locomotion," *Zoology*, vol. 109, no. 1, pp. 43–53, 2006, doi: 10.1016/j.zool.2005.11.001.

[22] F. Putzu, T. Abrar, and K. Althoefer, "Plant-inspired soft pneumatic eversion robot," in *Proc. 7th IEEE Int. Conf. Biomed. Robot. Biomechatron. (Biorob).*, 2018, pp. 1327–1332, doi: 10.1109/BIOROB.2018.8487848.

[23] U. Singla and S. Singh, "Semi-active control of automotive vehicle suspension system using magnetorheological damper-a review,"

Warrendale, PA, USA, SAE Technical Paper, Tech. Rep., 2004. doi: 10.4271/2004-28-0077.
[24] L. Segel and H. Lang, "The mechanics of automotive hydraulic dampers at high stroking frequencies," *Veh. Syst. Dynam.*, vol. 10, nos. 2–3, pp. 82–85, 1981, doi: 10.1080/00423118108968640.
[25] R. Sharp and D. Crolla, "Road vehicle suspension system design-a review," *Veh. Syst. Dynam.*, vol. 16, no. 3, pp. 167–192, 1987, doi: 10.1080/00423118708968877.
[26] M. Laffranchi, N. G. Tsagarakis, and D. G. Caldwell, "Compact arm: A compliant manipulator with intrinsic variable physical damping," in *Robotics: Science and Systems*. Cambridge, MA, USA: MIT Press, 2013, vol. 8, p. 225.
[27] D. Kim, J. Ahn, O. Campbell, N. Paine, and L. Sentis, "Investigations of a robotic test bed with viscoelastic liquid cooled actuators," *IEEE/ASME Trans. Mechatron.*, vol. 23, no. 6, pp. 2704–2714, 2018, doi: 10.1109/TMECH.2018.2872176.
[28] P. Song, Y. Yu, and X. Zhang, "Impedance control of robots: An overview," in *Proc. 2nd Int. Conf. Cybernetics, Robot. Control (CRC)*, 2017, pp. 51–55, doi: 10.1109/CRC.2017.20.
[29] F. J. Abu-Dakka and M. Saveriano, "Variable impedance control and learning—A review," 2020, arXiv:2010.06246.
[30] S. Haddadin, M. Weis, S. Wolf, and A. Albu-Schäffer, "Optimal control for maximizing link velocity of robotic variable stiffness joints," *IFAC Proc. Vol.*, vol. 44, no. 1, pp. 6863–6871, 2011, doi: 10.3182/20110828-6-IT-1002.01686.
[31] C. Yang, G. Ganesh, S. Haddadin, S. Parusel, A. Albu-Schaeffer, and E. Burdet, "Human-like adaptation of force and impedance in stable and unstable interactions," *IEEE Trans. Robot.*, vol. 27, no. 5, pp. 918–930, 2011, doi: 10.1109/TRO.2011.2158251.
[32] A. Radulescu, M. Howard, D. J. Braun, and S. Vijayakumar, "Exploiting variable physical damping in rapid movement tasks," in *Proc. IEEE/ASME Int. Conf. Adv. Intell. Mechatron. (AIM)*, 2012, pp. 141–148, doi: 10.1109/AIM.2012.6265889.
[33] Z. Shen and J. Seipel, "A fundamental mechanism of legged locomotion with hip torque and leg damping," *Bioinspiration Biomimetics*, vol. 7, no. 4, p. 046010, 2012, doi: 10.1088/1748-3182/7/4/046010.
[34] J. C. Doyle, K. Glover, and K. Zhou, *Robust and Optimal Control*. Englewood Cliffs, NJ, USA: Prentice-Hall, 1996, vol. 40.
[35] C. T. Landi, F. Ferraguti, L. Sabattini, C. Secchi, and C. Fantuzzi, "Admittance control parameter adaptation for physical human-robot interaction," in *Proc. IEEE Int. Conf. Robot. Automat. (ICRA)*, 2017, pp. 2911–2916, doi: 10.1109/ICRA.2017.7989338.
[36] F. Negrello *et al.*, "Humanoids at work: The walk-man robot in a postearthquake scenario," *IEEE Robot. Automat. Mag.*, vol. 25, no. 3, pp. 8–22, 2018, doi: 10.1109/MRA.2017.2788801.
[37] A. Mo, F. Izzi, D. F. Haeufle, and A. Badri-Spröwitz, "Effective viscous damping enables morphological computation in legged locomotion," 2020, arXiv:2005.05725.
[38] D. W. Weir, J. E. Colgate, and M. A. Peshkin, "Measuring and increasing Z-width with active electrical damping," in *Proc. Symp. Haptic Interfaces Virtual Environ. Teleoperator Syst.*, 2008, pp. 169–175, doi: 10.1109/HAPTICS.2008.4479938.
[39] J. E. Colgate and J. M. Brown, "Factors affecting the Z-width of a haptic display," in *Proc. IEEE Int. Conf. Robot. Automat.*, 1994, pp. 3205–3210, doi: 10.1109/ROBOT.1994.351077.
[40] S. Wolf *et al.*, "Variable stiffness actuators: Review on design and components," *IEEE/ASME Trans. Mechatron.*, vol. 21, no. 5, pp. 2418–2430, 2015, doi: 10.1109/TMECH.2015.2501019.
[41] M. Khabsa and C. L. Giles, "The number of scholarly documents on the public web," *PloS One*, vol. 9, no. 5, 2014, doi: 10.1371/journal.pone.0093949.
[42] A. Liberati *et al.*, "The prisma statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: Explanation and elaboration," *J. Clin. Epidemiol.*, vol. 62, no. 10, pp. e1–e34, 2009, doi: 10.1016/j.jclinepi.2009.06.006.
[43] J. Sun, M. R. Jolly, and M. Norris, "Passive, adaptive and active tuned vibration absorbers—A survey," *J. Mech. Des.*, vol. 117(B), pp. 234–242, Jun. 1995, doi: 10.1115/1.2836462.
[44] M. Laffranchi, N. G. Tsagarakis, and D. G. Caldwell, "Analysis and development of a semiactive damper for compliant actuation systems," *IEEE/ASME Trans. Mechatron.*, vol. 18, no. 2, pp. 744–753, 2012, doi: 10.1109/TMECH.2012.2184293.
[45] C. D. Silva, "An algorithm for the optimal design of passive vibration controllers for flexible systems," *J. Sound Vibration*, vol. 75, no. 4, pp. 495–502, 1981, doi: 10.1016/0022-460X(81)90437-5.
[46] G. Carpino, D. Accoto, M. Di Palo, N. L. Tagliamonte, F. Sergi, and E. Guglielmelli, "Design of a rotary passive viscoelastic joint for wearable robots," in *Proc. IEEE Int. Conf. Rehabil. Robot*, 2011, pp. 1–6, doi: 10.1109/ICORR.2011.5975356.
[47] T. Boaventura, G. A. Medrano-Cerda, C. Semini, J. Buchli, and D. G. Caldwell, "Stability and performance of the compliance controller of the quadruped robot HYQ," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2013, pp. 1458–1464, doi: 10.1109/IROS.2013.6696541.
[48] M. Laffranchi, N. G. Tsagarakis, and D. G. Caldwell, "A variable physical damping actuator (VPDA) for compliant robotic joints," in *Proc. IEEE Int. Conf. Robot. Automat.*, 2010, pp. 1668–1674, doi: 10.1109/ROBOT.2010.5509971.
[49] K. F. Laurin-Kovitz, J. E. Colgate, and S. D. Carnes, "Design of components for programmable passive impedance," in *Proc. IEEE Int. Conf. Robot. Automat.*, 1991, vol. 2, pp. 1476–1481, doi: 10.1109/ROBOT.1991.131824.
[50] M. Unsal, C. Niezrecki, and C. Crane, "Two semi-active approaches for vibration isolation: Piezoelectric friction damper and magnetorheological damper," in *Proc. IEEE Int. Conf. Mechatron. (ICM'04)*, 2004, pp. 60–65, doi: 10.1109/ICMECH.2004.1364413.
[51] E. Guglielmino, C. W. Staimmers, K. A. Edge, T. Sireteanu, and D. Stancioiu, "Damp-by-wire: Magnetorheological vs. friction dampers," *IFAC Proc. Vol.*, vol. 38, no. 1, pp. 340–345, 2005, doi: 10.3182/20050703-6-CZ-1902.01267.
[52] P. Constantin and C. Foias, *Navier-Stokes Equations*. Chicago, IL, USA: Univ. of Chicago Press, 1988.
[53] R. Feynman, R. Leighton, and M. Sands, *Feynman Lectures Physics*, 6th ed., vol. 2, 1977.
[54] M. G. Catalano, "Soft robotics: Design for simplicity, performance, and robustness of robots for interaction with humans," Ph.D. dissertation, Univ. Pisa, 2013.
[55] M. G. Catalano, "A variable damping module for variable impedance actuation," in *Proc. IEEE Int. Conf. Robot. Automat.*, 2012, pp. 2666–2672, doi: 10.1109/ICRA.2012.6224938.
[56] I. E. Idelchik, *Handbook of Hydraulic Resistance*. Washington, DC: Hemisphere Publishing Corp., 1986, p. 662.
[57] D. Accoto, N. L. Tagliamonte, G. Carpino, F. Sergi, M. Di Palo, and E. Guglielmelli, "pVEJ: A modular passive viscoelastic joint for assistive wearable robots," in *Proc. IEEE Int. Conf. Robot. Automat.*, 2012, pp. 3361–3366, doi: 10.1109/ICRA.2012.6225167.

[58] D. Zhi, Z. Feng, W. Xu, R. Kang, and L. Chen, "Design and control of a variable viscous damping actuator (VVDA) for compliant robotic joints," in *Proc. IEEE Int. Conf. Robot. Biomimetics (ROBIO)*, 2018, pp. 1876–1881, doi: 10.1109/ROBIO.2018.8665039.

[59] N. K. Petek, D. J. Romstadt, M. B. Lizell, and T. R. Weyenberg, "Demonstration of an automotive semi-active suspension using electrorheological fluid," *SAE Trans.*, vol. 104, pp. 987–992, 1995.

[60] A. Agrawal, P. Kulkarni, S. L. Vieira, and N. G. Naganathan, "An overview of magneto-and electro-rheological fluids and their applications in fluid power systems," *Int. J. Fluid Power*, vol. 2, no. 2, pp. 5–41, 2001, doi: 10.1080/14399776.2001.10781106.

[61] A. Khanicheh, D. Mintzopoulos, B. Weinberg, A. A. Tzika, and C. Mavroidis, "Evaluation of electrorheological fluid dampers for applications at 3-T MRI environment," *IEEE/ASME Trans. Mechatron.*, vol. 13, no. 3, pp. 286–294, 2008, doi: 10.1109/TMECH.2008.924043.

[62] J. Li, D. Jin, X. Zhang, J. Zhang, and W. A. Gruver, "An electrorheological fluid damper for robots," in *Proc. 1995 IEEE Int. Conf. Robot. Automat.*, 1995, vol. 3, pp. 2631–2636.

[63] X. Dong, W. Liu, X. Wang, J. Yu, and P. Chen, "Research on variable stiffness and damping magnetorheological actuator for robot joint," in *Proc. Int. Conf. Intell. Robot. Appl.*, 2017, pp. 109–119, doi: 10.1007/978-3-319-65298-6_11.

[64] N. Takesue, G. Zhang, M. Sakaguchi, J. Furusho, and Y. Kiyosawa, "Development and analysis of actuator with Er damper," in *Proc. ICRA Millennium Conf. IEEE Int. Conf. Robot. Automat.*, 2000, vol. 2, pp. 1328–1333, doi: 10.1109/ROBOT.2000.844782.

[65] C.-M. Chew, G.-S. Hong, and W. Zhou, "Series damper actuator: A novel force/torque control actuator," in *Proc. 4th IEEE/RAS Int. Conf. Humanoid Robots*, 2004, vol. 2, pp. 533–546, doi: 10.1109/ICHR.2004.1442669.

[66] T. Kikuchi, K. Ikeda, K. Otsuki, T. Kakehashi, and J. Furusho, "Compact MR fluid clutch device for human-friendly actuator," *J. Phys.: Conf. Ser.*, vol. 149, no. 1, p. 012059, 2009, doi: 10.1088/1742-6596/149/1/012059.

[67] R. Andrade, A. Bento Filho, C. Vimieiro, and M. Pinotti, "Optimal design and torque control of an active magnetorheological prosthetic knee," *Smart Mater. Struct.*, vol. 27, no. 10, p. 105031, 2018, doi: 10.1088/1361-665X/aadd5c.

[68] D. Wang and Y. Hou, "Design and experimental evaluation of a multidisk magnetorheological fluid actuator," *J. Intell. Mater. Syst. Struct.*, vol. 24, no. 5, pp. 640–650, 2013, doi: 10.1177/1045389X12470305.

[69] J. Furusho and T. Kikuchi, "A 3-d rehabilitation system for upper limbs "emul", and a 6-dof rehabilitation system "robotherapist", and other rehabilitation system with high safety," in *Rehabilitation Robotics*, S. S. Kommu, Rijeka, Croatia: I-Tech, 2007, pp. 115–136.

[70] E. Garcia, J. C. Arevalo, G. Muñoz, and P. Gonzalez-de Santos, "Combining series elastic actuation and magneto-rheological damping for the control of agile locomotion," *Robot. Autonom. Syst.*, vol. 59, no. 10, pp. 827–839, 2011, doi: 10.1016/j.robot.2011.06.006.

[71] R. Bell, E. Miller, J. Karli, A. Vavreck, and D. Zimmerman, "Influence of particle shape on the properties of magnetorheological fluids," *Int. J. Modern Phys. B*, vol. 21, nos. 28–29, pp. 5018–5025, 2007, doi: 10.1142/S0217979207045979.

[72] J. E. Stangroom, "Electrorheological fluids," *Phys. Technol.*, vol. 14, no. 6, p. 290, 1983, doi: 10.1088/0305-4624/14/6/305.

[73] Z. Huang, X. Hua, Z. Chen, and H. Niu, "Modeling, testing, and validation of an eddy current damper for structural vibration control," *J. Aerospace Eng.*, vol. 31, no. 5, p. 04018063, 2018, doi: 10.1061/(ASCE)AS.1943-5525.0000891.

[74] H. A. Sodano, J.-S. Bae, D. J. Inman, and W. K. Belvin, "Improved concept and model of eddy current damper," *J. Vib. Acoust.*, vol. 128, no. 3, pp. 294–302, Jun. 2006.

[75] B. Ebrahimi, M. B. Khamesee, and F. Golnaraghi, "A novel eddy current damper: Theory and experiment," *J. Phys. D, Appl. Phys.*, vol. 42, no. 7, p. 075001, 2009, doi: 10.1088/0022-3727/42/7/075001.

[76] A. H. Gosline, G. Campion, and V. Hayward, "On the use of eddy current brakes as tunable, fast turn-on viscous dampers for haptic rendering," *Proc. Eurohaptics*, vol. 2006, pp. 229–234, 2006.

[77] A. H. Gosline and V. Hayward, "Eddy current brakes for haptic interfaces: Design, identification, and control," *IEEE/ASME Trans. Mechatron.*, vol. 13, no. 6, pp. 669–677, 2008, doi: 10.1109/TMECH.2008.2004623.

[78] J. J. Martin, J. Schulz, P. Chaubey, and C. Haslam, "Passive electromagnetically damped joint," Jul. 30, 2009, U.S. Patent Appl. 12/313,620.

[79] F. Wu and M. Howard, "Energy regenerative damping in variable impedance actuators for long-term robotic deployment," *IEEE Trans. Robot.*, vol. 36, no. 6, pp. 1778–1790, 2020, doi: 10.1109/TRO.2020.2998641.

[80] B. Bhushan and B. K. Gupta, *Handbook of Tribology: Materials, Coatings, and Surface Treatments*, New York, NY, USA: McGraw Hill, 1991.

[81] G. M. Bartenev and Y. S. Zuyev, *Strength and Failure of Visco-Elastic Materials*. Amsterdam, The Netherlands: Elsevier, 2013.

[82] D. Chiaradia, L. Tiseni, and A. Frisoli, "Compact series visco-elastic joint (svej) for smooth torque control," *IEEE Trans. Haptics*, vol. 13, no. 1, pp. 226–232, 2020, doi: 10.1109/TOH.2020.2970912.

[83] L. Sentis and N. Paine, "Viscoelastic liquid-cooled actuator," U.S. Patent Appl. 15/604,431, Nov. 30, 2017.

[84] N. E. Wiltsie, "Characterization of a series viscous actuator for use in rehabilitative robotics," Ph.D. dissertation, Massachusetts Inst. of Technol., 2010.

[85] M. Laffranchi, L. Chen, N. Kashiri, J. Lee, N. G. Tsagarakis, and D. G. Caldwell, "Development and control of a series elastic actuator equipped with a semi active friction damper for human friendly robots," *Robot. Autonom. Syst.*, vol. 62, no. 12, pp. 1827–1836, 2014, doi: 10.1016/j.robot.2014.06.007.

[86] I. Sarakoglou, N. G. Tsagarakis, and D. G. Caldwell, "Development of a hybrid actuator with controllable mechanical damping," in *Proc. IEEE Int. Conf. Robot. Automat. (ICRA)*, 2014, pp. 1078–1083, doi: 10.1109/ICRA.2014.6906988.

[87] N. Kashiri, G. A. Medrano-Cerda, N. G. Tsagarakis, M. Laffranchi, and D. Caldwell, "Damping control of variable damping compliant actuators," in *Proc. IEEE Int. Conf. Robot. Automat. (ICRA)*, 2015, pp. 850–856, doi: 10.1109/ICRA.2015.7139277.

[88] N. Kashiri, M. Laffranchi, D. G. Caldwell, and N. G. Tsagarakis, "Dynamics and control of an anthropomorphic compliant arm equipped with friction clutches," *IEEE/ASME Trans. Mechatron.*, vol. 21, no. 2, pp. 694–707, 2015, doi: 10.1109/TMECH.2015.2497200.

[89] N. Kashiri, D. G. Caldwell, and N. Tsagarakis, "A self-adaptive variable impedance actuator based on intrinsic non-linear compliance and damping principles," in *Proc. IEEE Int. Conf. Robot. Automat. (ICRA)*, 2017, pp. 1248–1254, doi: 10.1109/ICRA.2017.7989148.

[90] N. Lauzier and C. Gosselin, "Series clutch actuators for safe physical human-robot interaction," in *Proc. IEEE Int. Conf. Robot. Automat.*, 2011, pp. 5401–5406, doi: 10.1109/ICRA.2011.5979601.

[91] N. L. Tagliamonte, F. Sergi, G. Carpino, D. Accoto, and E. Guglielmelli, "Design of a variable impedance differential actuator for wearable robotics applications," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2010, pp. 2639–2644, doi: 10.1109/IROS.2010.5649982.
[92] J. Malzahn, V. D. Amara, and N. Tsagarakis, "Continuously controllable series clutches for efficient robot actuation," in *Proc. IEEE Int. Conf. Robot. Automat. (ICRA)*, 2018, pp. 7735–7741, doi: 10.1109/ICRA.2018.8463192.
[93] J. W. Sensinger, L. E. Burkart, G. A. Pratt, and R. F. ff. Weir, "Effect of compliance location in series elastic actuators," *Robotica*, vol. 31, no. 8, pp. 1313–1318, 2013, doi: 10.1017/S0263574713000532.
[94] N. Karavas, A. Ajoudani, N. Tsagarakis, J. Saglia, A. Bicchi, and D. Caldwell, "Tele-impedance based assistive control for a compliant knee exoskeleton," *Robot. Autonom. Syst.*, vol. 73, pp. 78–90, Nov. 2015, doi: 10.1016/j.robot.2014.09.027.
[95] A. Werner, W. Turlej, and C. Ott, "Generation of locomotion trajectories for series elastic and viscoelastic bipedal robots," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, 2017, pp. 5853–5860, doi: 10.1109/IROS.2017.8206476.
[96] T. Morita and S. Sugano, "Design and development of a new robot joint using a mechanical impedance adjuster," in *Proc. IEEE Int. Conf. Robot. Automat.*, vol. 3, pp. 2469–2475, 1995, doi: 10.1109/ROBOT.1995.525630.
[97] E. Westervelt, J. Schmiedeler, and G. Washington, "Variable transmission compliance with an Mr Damper," in *Proc. Int. Mech. Eng. Congr. Expo.*, 2004, pp. 241–246, doi: 10.1115/IMECE2004-62046.
[98] H. Herr, S. Au, P. Dilworth, and D. Paluska, "Artificial ankle-foot system with spring, variable-damping, and series-elastic actuator components," Feb. 22, 2007, U.S. Patent Appl. 11/495,140.
[99] R. M. Ahmed, I. G. Kalaykov, and A. V. Ananiev, "Modeling of magneto rheological fluid actuator enabling safe human-robot interaction," in *Proc. IEEE Int. Conf. Emerg. Technol. Factory Automat.*, 2008, pp. 974–979, doi: 10.1109/ETFA.2008.4638512.
[100] C. Khazoom, P. Caillouette, A. Girard, and J.-S. Plante, "A supernumerary robotic leg powered by magnetorheological actuators to assist human locomotion," *IEEE Robot. Automat. Lett.*, vol. 5, no. 4, 2020, doi: 10.1109/LRA.2020.3005629.
[101] M. Laffranchi, N. Tsagarakis, and D. G. Caldwell, "A compact compliant actuator (CompAct™) with variable physical damping," in *Proc. IEEE Int. Conf. Robot. Automat.*, 2011, pp. 4644–4650.
[102] P. Fauteux, M. Lauria, B. Heintz, and F. Michaud, "Dual-differential rheological actuator for high-performance physical robotic interaction," *IEEE Trans. Robot.*, vol. 26, no. 4, pp. 607–618, 2010, doi: 10.1109/TRO.2010.2052880.
[103] F. Murtagh and P. Contreras, "Algorithms for hierarchical clustering: An overview," *Wiley Interdisciplinary Rev.: Data Mining Knowl. Discovery*, vol. 2, no. 1, pp. 86–97, 2012, doi: 10.1002/widm.53.
[104] R. L. Devengenzo, B. M. Schena, and D. W. Robinson, "Active and semi-active damping in a telesurgical system," Aug. 28, 2018, U.S. Patent 10 058 395.
[105] C. Colomer *et al.*, "Efficacy of armeo® spring during the chronic phase of stroke. study in mild to moderate cases of hemiparesis," *Neurologia (English Edition)*, vol. 28, no. 5, pp. 261–267, 2013, doi: 10.1016/j.nrleng.2012.04.017.
[106] H. Kazerooni, "Exoskeletons for human power augmentation," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2005, pp. 3459–3464, doi: 10.1109/IROS.2005.1545451.
[107] C. Pacchierotti, S. Sinclair, M. Solazzi, A. Frisoli, V. Hayward, and D. Prattichizzo, "Wearable haptic systems for the fingertip and the hand: Taxonomy, review, and perspectives," *IEEE Trans. Haptics*, vol. 10, no. 4, pp. 580–600, 2017, doi: 10.1109/TOH.2017.2689006.
[108] Ts 15066: 2016: Robots and *Robotic Devices–Collaborative Robots*. International Organization for Standardization, Geneva, Switzerland, 2016.
[109] P. Scholl, V. Grabosch, M. Eslamy, and A. Seyfarth, "Comparison of peak power and energy requirements in different actuation concepts for active knee prosthesis," in *Proc. IEEE Int. Conf. Mechatron. Automat. (ICMA)*, 2015, pp. 1448–1453, doi: 10.1109/ICMA.2015.7237698.
[110] Y. Huang *et al.*, "Step length and velocity control of a dynamic bipedal walking robot with adaptable compliant joints," *IEEE/ASME Trans. Mechatron.*, vol. 18, no. 2, pp. 598–611, 2012, doi: 10.1109/TMECH.2012.2213608.
[111] F. Ameri, J. D. Summers, G. M. Mocko, and M. Porter, "Engineering design complexity: An investigation of methods and measures," *Res. Eng. Design*, vol. 19, nos. 2–3, pp. 161–179, 2008, doi: 10.1007/s00163-008-0053-2.
[112] J. C. Mankins, "Technology readiness levels," American Institute of Aeronautics and Astronautics, Reston, VA, USA, White Paper, Apr. 6, 1995.
[113] D. Surdilovic, G. Schreck, and U. Schmidt, "Development of collaborative robots (COBOTS) for flexible human-integrated assembly automation," in *Proc. ISR 2010 (41st Int. Symp. Robot.) ROBOTIK 2010 (6th German Conf. Robot.)*, 2010, pp. 1–8.
[114] G. M. Whitesides, "Soft robotics," *Angewandte Chemie Int. Ed.*, vol. 57, no. 16, pp. 4258–4273, 2018, doi: 10.1002/anie.201800907.
[115] *Robots and Robotic Devices – Safety Requirements for Industrial Robots*.
[116] S. Haddadin, A. Albu-Schäffer, and G. Hirzinger, "Requirements for safe robots: Measurements, analysis and new insights," *Int. J. Robot. Res.*, vol. 28, nos. 11–12, pp. 1507–1527, 2009, doi: 10.1177/0278364909343970.
[117] R. F. Kirsch, D. Boskov, and W. Z. Rymer, "Muscle stiffness during transient and continuous movements of cat muscle: Perturbation characteristics and physiological relevance," *IEEE Trans. Biomed. Eng.*, vol. 41, no. 8, pp. 758–770, 1994, doi: 10.1109/10.310091.

Simone Monteleone, Research Center "E. Piaggio" and Department of Information Engineering, University of Pisa, Pisa, Italy, 56126. Email: monteleone.simone.sm@gmail.com.

Francesca Negrello, Italian Institute of Technology, Genoa, 16163, Italy. Email: francesca.negrello@gmail.com.

Manuel G. Catalano, Italian Institute of Technology, Genoa, 16163, Italy. Email: manuel.catalano@iit.it.

Manolo Garabini, Research Center "E. Piaggio" and Department of Information Engineering, University of Pisa, Pisa, Italy, 56126. Email: manolo.garabini@gmail.com.

Giorgio Grioli, Italian Institute of Technology, Genoa, 16163, Italy. Email: giorgio.grioli@gmail.com.