AVASTT: A New Variable Stiffness Actuator with Torque Threshold

J. López Martínez[1], J.L. Blanco[1], D. García Vallejo[2],
J.L. Torres[1], and A. Giménez Fernández[1]

[1] Department of Engineering, University of Almería, Spain
javier.lopez@ual.es
[2] Department of Mechanical Engineering and Materials, University of Seville, Spain

Abstract. Variable Stiffness Actuators (VSAs) emerged as an alternative to conventional actuators in a variety of applications, such as walking robots and service robotics. New requirements, which were obviated in the design of rigid actuators, must be accounted for during the mechanical design of such new devices. Among them, we find the possibility of tunning the natural frequency of the mechanical system or damage reduction in case of impacts A multitude of solutions have been already proposed in the literature, each characterized by the kind of mechanism in charge of implementing the equilibrium position and the stiffness of the joint. With this work, we introduce a new actuator design based on tendon transmission, where a main motor controls the equilibrium position of the link while a secondary motor is in charge of modifying the joint stiffness. Unlike existing actuators, our proposal achieves a wide range of stiffness values, from close to zero up to completely rigid. Another distinguishing feature of the new design is the existence of a torque threshold, such that variable stiffness only becomes effective once the load is above a certain predefined threshold.

1 Introduction

In recent years, advance in the variable stiffness actuators (VSA) has been notable in the robotic field. Several designs of VSA have been proposed and studied the performance in different applications.

The concept of a VSA is to elastically decouple the link inertia and the motor rotor inertia, where the stiffness of the coupling can be modified and controlled. This mechanical implementation has two main applications. On the one hand, the elastic component of the variable stiffness mechanism allows to store and release energy, reducing the energy consumption and maximizing the velocity peak torque achievable with a classical "stiff" actuator. Here, the capability of modify the stiffness of the joint is needed to adjust the natural frequency of the system. The most relevant application is in walking and running robots and in robotic prosthesis, where by varying the stiffness of the mechanism, the natural frequency is modified and adjusted to different step frequency [1–4]. Also, the capability of store and release energy can be used to achieve faster movements

M.A. Armada et al. (eds.), *ROBOT2013: First Iberian Robotics Conference*, Advances in Intelligent Systems and Computing 252,
DOI: 10.1007/978-3-319-03413-3_42,

of a robot arm. In a rigid actuator the link speed is the same of the motor, but in a flexible joint, the potential energy can be used to accelerate the link with respect the output shaft of the motor. Albu-Shäffer et al. [5] have experimentally confirmed a speed gain of 265% for the link velocity between a rigid and an elastic joint.

On the other hand, the VSA can be used as a safety mechanism. Since the VSA decouples the rotor inertia from the link inertia, the rotor inertia and the inertia of the rest of the links of the kinematic chain do not take part in case of an unexpected impact with the environment. This mean lower impact forces for the safety of the environment, or for the human safety in the case of a service or an assistive robot, and lower joint peak torque for joint protection. For a safety robot, the VSA can be act stiff during precise tasks at low speeds and compliant in fast movements when positioning is not important [6].

As a result of works carried out in different robotic fields where VSAs find applications, a large number of designs have been proposed. According to the functional concept and disposition of the flexible components of the VSA, they can be classified into antagonistic configuration or serial configuration. In the antagonistic configuration, two elastic elements act in opposite directions at the joint, and the equilibrium position and the stiffness of the joint are controlled by two motors. In the majority of antagonist configurations, motors only act over one of the two elastic components, so that motors also act in opposite directions jointly changing both the position and the stiffness of the joint [7, 8]. Nevertheless, under the point of view of energy efficiency it becomes desirable to use each motor for one independent task [9]; in those cases, a first motor controls the link position while another one changes the joint stiffness [10, 11]. In the serial configuration only one flexible element is required between the main motor, in charge of settling the equilibrium position, and the link; a second, smaller motor, modifies the stiffness [12–15, 4].

The present work introduces the design of a novel VSA, named *AVASTT* (Actuator with VAriable Stiffness and Torque Threshold), whose working principles rely on tendon transmission, and set it apart from previous similar devices due to the wide stiffness range, from close to zero up to ideally rigid; and the existence of a torque threshold, where the compliance of the actuator only acts when the external torque reach a predefined minimun value. In section 2 we firstly review the desiderata regarding design criteria of this kind of actuators. Next, our proposed design is introduced and a mathematical modeling is derived in section 3, while the next section describes our practical implementation of a physical prototype. We end providing some conclusions in section 6.

2 Design Criteria

The most relevant design criteria of a rigid actuator are the maximum torque that the driving motor should provide and the maximum rotational speed. In contrast, new important characteristic must be taken into account when dealing with VSA:

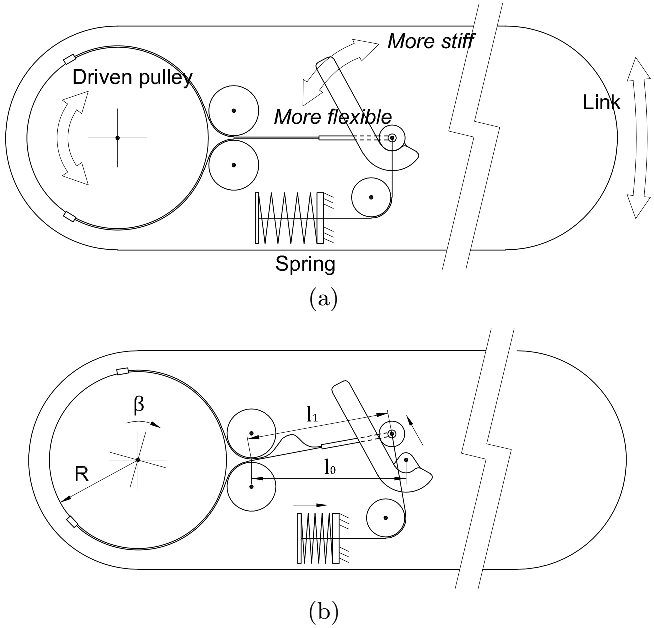


Fig. 1. The conceptual design of our VSA, (a) in its rest configuration and (b) deformed under an external force

- Allowed stiffness range.
- Permitted range for the angular deviation.
- Dependence between stiffness and angular deviation.
- Energy storage capability.

The characteristics of the different kinds of VSAs are strongly conditioned by the specific type of mechanism employed to control the position and stiffness of the actuator. Apart from the classification into antagonist versus serial configuration, another key feature of VSAs is the way in which stiffness is actually modified. The most frequently-adopted solution is the pretension of the flexible component, usually a spring, which by means of the appropriate mechanism becomes a variation of the actuator stiffness. However, an important drawback of this approach is that the motor must operate working against the flexible element [7, 8, 10, 11, 13, 14, 4]. Different proposals that can be found in the literature rely on the modification of the length of a lever, thus maintaining the pretension of the elastic component constant during operation [12, 15].

Next we address the main aspects of the above mentioned VSA properties:

- **Allowed stiffness range.** It is defined by the minimum and maximum stiffness values allowed by the device. Although this range may depend on the particular application, in principle it would be desirable to have the largest possible range. Most previously-proposed VSAs have a limited stiffness range and only a few proposals (e.g. those based on the variation of the lever length) can reach a totally rigid configuration. Among those ones, AWAS-II [15] can also achieve, at least in theory, a null stiffness.

- **Range of angular deviation.** This is the range of the potential angles between the equilibrium position and that of the link under external loads. The mechanism should allow a range of angles wide enough such that, during normal operation, it does not reach its mechanical limit positions. A deviation of 15° is considered enough for humanoid robot arms [11].
- **Dependence between stiffness and angular deviation** (stiffness curve), that is, how the stiffness varies as the angular deviation increases. In applications where the goal is reducing the damage caused by a potential impact between the robot and a human, increasing stiffness is preferable [11, 13–15]. An stiffness that increases with deformation has been also found to be desirable in active prostheses and in hopping robots [4].
- **Energy storage capability.** This property is closely related to the range of angular deviation and the stiffness curve. The overall elastic potential energy could be employed to absorb kinetic energy in an impact or to intentionally accelerate the link motion by means of a proper control strategy [11].

3 Mathematical Modeling

In this section we first describe the working principles of our new AVASTT actuator, then derive a suitable mathematical model for it. We must remark that during the design phase we took in mind all the aspects mentioned in the previous section.

The proposed mechanism comprises a serial configuration, with the driving rotor determining the equilibrium position of the output link and a secondary motor to modify the stiffness of the joint. Fig. 1 illustrates the conceptual design, whose main characteristic is the usage of a tendon-pulley transmission. The output shaft of the motor is attached to the driving pulley, which has two wires attached each with its own tensioner. In turn, the cables are attached to an internal rigid rod whose end is pinned to a cylinder that can freely roll over a lever. A third tendon is attached between the cylinder axis and a spring that is attached to the link frame.

When a torque is applied by the motor shaft, the spring is compressed. This elastic deformation leads to the angular deviation β between the shaft motor position and the output link –refer to Fig. 1(b). The value of this angle clearly reflects the degree of stiffness of our VSA, and is determined by the angular position of the lever actuated by the secondary motor. When the lever is exactly in the vertical position, according to Fig. 1(a), the actuator becomes an ideal rigid actuator since no angular offset is allowed between the input and the output link. On the other hand, when the lever is horizontal we achieve maximum flexibility. Notice that Fig. 1(a)–(b) show two different states of our design for the same configuration of the internal lever, i.e. constant stiffness, but with a zero and a nonzero input torque, respectively.

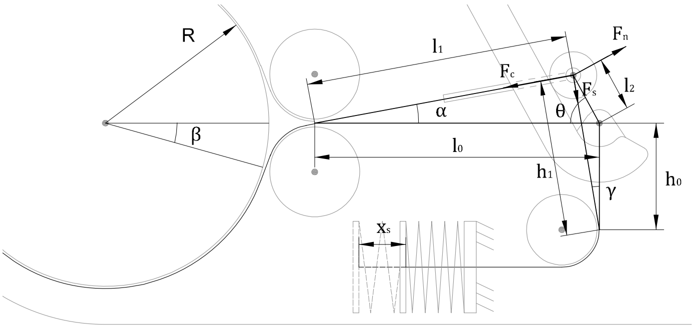


Fig. 2. Schematic description of all the variables involved in the analysis of our VSA

In order to properly characterize our actuator we must obtain the relationship between the actuating torque T and the resulting angle β. Please, refer to Fig. 2 for the physical meaning of all the variables that we present next while searching for the relationship between the angular deviation β and the torque T and the stiffness K.

When the driving pulley rotates an angle β with respect to the equilibrium position, and neglecting the elastic elongation of the tendons, it is clear that part of the initial length l_0 will move towards the pulley (in particular, a length of βR) while the rest must match the final length of the cable (l_1 in the figure). Therefore,

$$l_0 = l_1 + \beta R \tag{1}$$

In this new position, the cylinder has rolled over the lever a distance l_2, which depends on the angular position of the lever. Let θ be this parameter that controls the stiffness of our actuator. Then, the angle α can be obtained from the triangle with sides l_0, l_1 and l_2 as:

$$\sin\alpha = \frac{l_2 \sin\theta}{l_1} \tag{2}$$

and regarding the rolling distance l_2, it can also be obtained from the cosine rule applied to the same triangle, which leads to:

$$\begin{aligned} & l_1^2 = (l_2 \sin\theta)^2 + (l_0 - l_2 \cos\theta)^2 \\ \longrightarrow \quad & l_2 = l_0 \cos\theta - \sqrt{l_1^2 - l_0^2 \sin^2\theta} \end{aligned} \tag{3}$$

The displacement of the cylinder generates a spring compression of:

$$x_s = h_1 - h_0 \tag{4}$$

with h_0 and h_1 the initial and final cable lengths as depicted in Fig. 2. It can be then shown that:

$$h_1 = \sqrt{(l_1 \sin\alpha + h_0)^2 + \left(\frac{l_1 \sin\alpha}{\tan\theta}\right)^2} \tag{5}$$

By now substituting (1), (2) and (3) into (5), then the resulting expression into (4), we arrive at the expression that relates the spring compression x_s with the angular torsion β,

$$x_s = \sqrt{A^2 + h_0^2 - 2\mathbf{h}_0 A \sin\theta} - h_0 \tag{6}$$

$$\text{with: } A = \sqrt{(l_0 - R\beta)^2 - l_0^2 \sin^2\theta} - l_0 \cos\theta$$

Next we address the evaluation of the torque T from the spring elastic force. The tension of the spring tendon is simply its stiffness K_s times the deformation, i.e.

$$F_s = K_s x_s \tag{7}$$

Three different forces act on the rolling cylinder: (i) the force F_s above, (ii) a reaction force F_n, normal to the lever, and (iii) the tension F_c from the tendon attached to the driving pulley. Solving for force equilibrium we arrive at:

$$F_c = F_s \frac{\sin(\theta + \gamma)}{\cos(\theta + \alpha)} \tag{8}$$

with the angle γ given by:

$$\gamma = \tan^{-1} \frac{l_2 \cos\theta}{h_0 + l_2 \sin\theta} \tag{9}$$

Finally, the torque T can be written as (the complete expression is not shown for the sake of conciseness):

$$T = F_c R = T(R, l_0, h_0, K_s, \theta, \beta), \tag{10}$$

and taking derivatives of (11) with respect to β we obtain the torsional stiffness of our actuator:

$$K = \frac{dT}{d\beta} = K(R, l_0, h_0, K_s, \theta, \beta), \tag{11}$$

Thus, both the torque T and the stiffness K depend on a number of parameters: mechanism dimensions (R,l_0,h_0), the linear stiffness of the spring (K_s), the lever angle (θ) and the angular deviation (β). For any given actuator the first four parameters will remain fixed, while the lever position θ will be controlled with the secondary motor. As previosuly introduced, when the lever is in the vertical position (i.e. (θ)=0 deg) no angular deviation is mechanically allowed, then the actuator is completely rigid. In the opposite behaviour, if the lever is horizontal (i.e. (θ)=0 deg), no force is requiered at the beginning of the angular deviation (as derived from (8)), hence null stiffness is showed. Others main properties of the proposed VSA are summarized besides the mechanical implementation in 5.

4 Torque Threshold

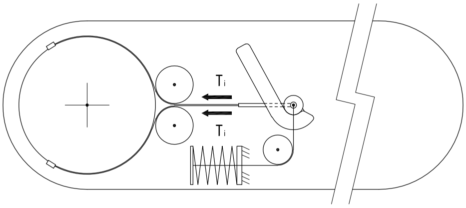
A singular feature of the AVASTT is the possibility of adjust a torque threshold. In this configuration, the joint act as a rigid one since the external force applied in the link do not overtakes a selected threshold. Once this value is exceeded the compliance of the mechanism comes into operation. With this feature, the robot can work as a rigid robot in precise positioning tasks assuring the joint protection in case of an external overload. Also, in a compliant configuration of the VSA, a slight torque threshold makes the joint more stable without losing its benefits of store and release energy.

In AVASTT the threshold torque can be adjusted with the tensioner of the wires. If the wires have an initial pretension, in the equilibrium position of the joint the two wires have the same value of tension. When an external force is applied at the link, the tension of one of the two wires start increasing, while is decreasing in the other wire (Fig. 3). Until the first wire has doubled the initial tension and the second one is loosed the spring do not start compression. Then, adjusting the wires initial tension it can be modified the torque threshold at which the compliant actuator acts.

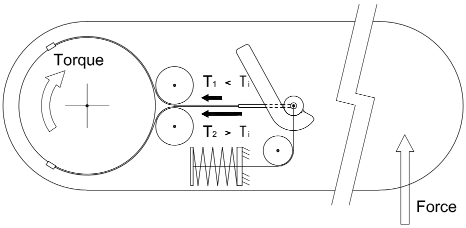
5 Mechanical Implementation

Fig. 4 illustrates the mechanical implementation of the AVASTT. The driving (main) motor is a Maxon DC motor with a nominal torque of 0.4 Nm, coupled to a planetary gearhead with a gear ratio of 100:1. As a secondary motor we employ a Maxon DC motor with a peak torque of 0.14 Nm. The latter motor acts on the lever that controls the system stiffness by means of a non-reversible worm drive with a ratio of 60:1. The linear spring has a stiffness of 80.5 kN/m and a maximum length compression of 34 mm, which limits the angular deviation (β) of the mechanism to a maximum of 54°, when used in its minimum-stiffness configuration.

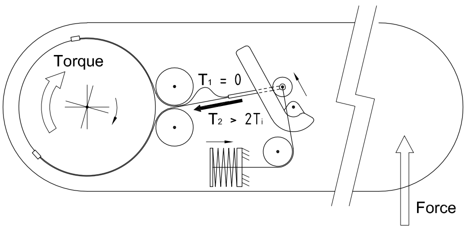
We present in Fig. 5(a) a number of torque vs. angular deviation curves for different configurations of our VSA (i.e. different positions of the inner lever), which have been computed with the nominal dimensions of our prototype ($R = 7$ cm, $l_0 = 151$ mm, $h_0 = 47$ mm). It can be seen how the curves present an increasing slope as the lever angle increases, becoming totally vertical when the mechanism limit is reached, that is, when the pulley cable becomes perpendicular to the lever. Fig. 5(b) shows the stiffness curves, which also exhibit the same behavior of increasing with the angular deviation. A comparative between the main characteristics of our prototype and other representative VSA can be found in Table 1. Notice that the dimensions of this first prototype have been largely overestimated in order to make it resistant to severe impact tests. A lighter and more compact design is feasible in order to make it suitable for integration into humanoid robots.



(a)

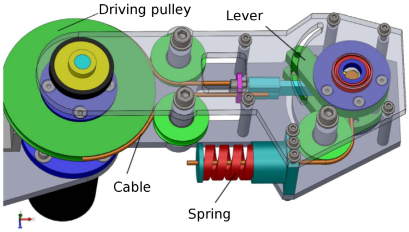


(b)

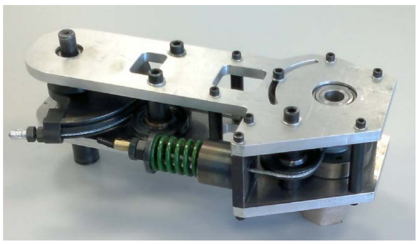


(c)

Fig. 3. Illustration of how pretensioning of the inner cables can be exploited to achieve a torque threshold in the behavior of the actuator. a) Equilibrium position. Wires initial pretension. b) Applied external force below the threshold limit. c) Applied external force over the threshold limit, VSA actuation.



(a)

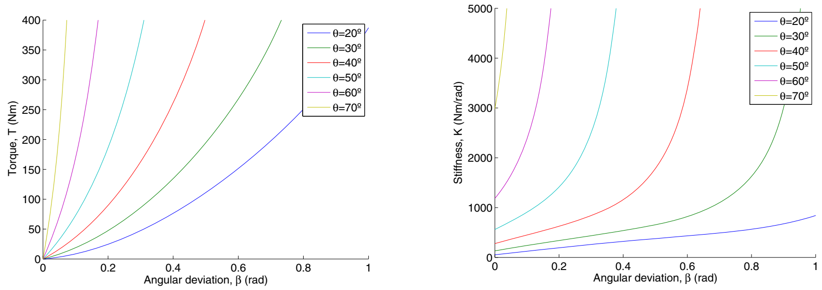


(b)

Fig. 4. (a) CAD model and (b) real picture of our VSA design, without the motors

Table 1. Comparison of the AVASTT prototype with other VSAs

	AVASTT (This work)	AwAS [16]	AwAS-II [15]	FSJ [16]	MACCEPA [2]	VSA-CUBE [17]	VSA-HD [18]
Nominal torque (Nm)	40	10.75	10.75	31.3	50	1.1	10
Maximum stiffness (Nm/rad)	∞	1300	∞	826	110	14	8360
Minimum stiffness (Nm/rad)	0	30	0	52.4	5	3	0.38
Maximum elastic energy (J)	46	3.5	5.8	5.3	27.9	0.047	0.12
Maximum deflection (°)	54	14	17	15	60	16	60
Active rotation angle (°)	360	120	150	180	150	120	360
Mass (kg)	4.5	1.8	1.4	1.41	2.4	0.26	1.7



(a) (b)

Fig. 5. (a) Torque-angle and (b) stiffness-angle curves for our prototype

6 Conclusions

With this work we have introduced a new VSA design. We opted for a serial configuration design, where a main motor drives the actuator while a secondary one is in charge of modifying the stiffness by means of rotating an inner lever. Our design allows fulfilling with the imposed design requisites, with a wide range of achievable stiffness, even allowing a complete rigidity. One particularity of the presented model is the possibility of adjust a torque threshold, with this feature the compliance of the joint only acts when the external force overtakes a certain level. Future works will address an extensive experimental validation of the physical prototype in order to verify its predicted properties.

Acknowledgements. This work has been partially funded by the Spanish "Ministerio de Ciencia e Innovación" under the contract "DAVARBOT" (DPI 2011-22513) and the grant program JDC-MICINN 2011, as well as by the Andalusian Regional Government grant programs FPDU 2008 and FPDU 2009, cofinanced by the European Union through the European Regional Development Fund (ERDF).

References

1. Hurst, J.W., Chestnutt, J.E., Rizzi, A.A.: An actuator with physically variable stiffness for highly dynamic legged locomotion. In: IEEE International Conference on Robotics and Automation (ICRA), vol. 5, pp. 4662–4667. IEEE (2004)

2. Van Ham, R., Vanderborght, B., Van Damme, M., Verrelst, B., Lefeber, D.: Maccepa, the mechanically adjustable compliance and controllable equilibrium position actuator: Design and implementation in a biped robot. Robotics and Autonomous Systems 55(10), 761–768 (2007)
3. Sugar, T.G., Hollander, K.W., Hitt, J.K.: Walking with springs. In: SPIE Smart Structures and Materials+ Nondestructive Evaluation and Health Monitoring, International Society for Optics and Photonics, pp. 797602–797602 (2011)
4. Vanderborght, B., Tsagarakis, N.G., Semini, C., Van Ham, R., Caldwell, D.G.: Maccepa 2.0: Adjustable compliant actuator with stiffening characteristic for energy efficient hopping. In: IEEE International Conference on Robotics and Automation (ICRA), pp. 544–549. IEEE (2009)
5. Albu-Schaffer, A., Eiberger, O., Grebenstein, M., Haddadin, S., Ott, C., Wimbock, T., Wolf, S., Hirzinger, G.: Soft robotics. IEEE Robotics & Automation Magazine 15(3), 20–30 (2008)
6. Bicchi, A., Tonietti, G.: Fast and "soft-arm" tactics. IEEE Robotics & Automation Magazine, 22–33 (2004)
7. Migliore, S.A., Brown, E.A., DeWeerth, S.P.: Biologically inspired joint stiffness control. In: IEEE International Conference on Robotics and Automation (ICRA), pp. 4508–4513. IEEE (2005)
8. Schiavi, R., Grioli, G., Sen, S., Bicchi, A.: Vsa-ii: A novel prototype of variable stiffness actuator for safe and performing robots interacting with humans. In: IEEE International Conference on Robotics and Automation (ICRA), pp. 2171–2176. IEEE (2008)
9. Vanderborght, B., Van Ham, R., Lefeber, D., Sugar, T.G., Hollander, K.W.: Comparison of mechanical design and energy consumption of adaptable, passive-compliant actuators. The International Journal of Robotics Research 28(1), 90–103 (2009)
10. Hurst, J.W., Chestnutt, J.E., Rizzi, A.A.: The actuator with mechanically adjustable series compliance. IEEE Transactions on Robotics 26(4), 597–606 (2010)
11. Eiberger, O., Haddadin, S., Weis, M., Albu-Schaffer, A., Hirzinger, G.: On joint design with intrinsic variable compliance: Derivation of the dlr qa-joint. In: IEEE International Conference on Robotics and Automation (ICRA), pp. 1687–1694. IEEE (2010)
12. Kim, B.S., Song, J.B.: Hybrid dual actuator unit: A design of a variable stiffness actuator based on an adjustable moment arm mechanism. In: IEEE International Conference on Robotics and Automation (ICRA), pp. 1655–1660. IEEE (2010)
13. Hyun, D., Yang, H.S., Park, J., Shim, Y.: Variable stiffness mechanism for human-friendly robots. Mechanism and Machine Theory 45(6), 880–897 (2010)
14. Wolf, S., Hirzinger, G.: A new variable stiffness design: Matching requirements of the next robot generation. In: IEEE International Conference on Robotics and Automation (ICRA), pp. 1741–1746. IEEE (2008)
15. Jafari, A., Tsagarakis, N.G., Caldwell, D.G.: Awas-ii: A new actuator with adjustable stiffness based on the novel principle of adaptable pivot point and variable lever ratio. In: IEEE International Conference on Robotics and Automation (ICRA), pp. 4638–4643. IEEE (2011)
16. Wolf, S., Eiberger, O., Hirzinger, G.: The dlr fsj: Energy based design of a variable stiffness joint. In: IEEE International Conference on Robotics and Automation (ICRA), pp. 5082–5089. IEEE (2011)

17. Catalano, M.G., Grioli, G., Garabini, M., Bonomo, F., Mancinit, M., Tsagarakis, N., Bicchi, A.: Vsa-cubebot: A modular variable stiffness platform for multiple degrees of freedom robots. In: IEEE International Conference on Robotics and Automation (ICRA), pp. 5090–5095. IEEE (2011)
18. Catalano, M.G., Grioli, G., Bonomo, F., Schiavi, R., Bicchi, A.: Vsa-hd: From the enumeration analysis to the prototypical implementation. In: IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), pp. 3676–3681. IEEE (2010)