Series Elastic Actuation: Potential and Pitfalls*

Jonathan W. Hurst and Alfred A. Rizzi
The Robotics Institute
Carnegie Mellon University
Pittsburgh, Pennsylvania
{*jhurst, arizzi*}*@ri.cmu.edu*

Daan Hobbelen
Department of Mechanical Engineering
Delft University of Technology
Netherlands
D.G.E.hobbelen@wbmt.tudelft.nl

***Abstract*—In this paper we explore the space of design freedoms associated with series elastic actuators. We specifically focus on the problem of damping, and evaluate through simulation how inclusion of series damping can improve the reliability and controllability of tasks involving force control and impact. We explicitly build upon the pioneering work by Pratt and colleagues at the MIT Leg Lab in the mid to late 1990s, and seek to define metrics for evaluating performance of series elastic actuation systems. The conclusion demonstrates the utility of including well tuned damping in such systems.**

***Index Terms*—Actuator Force Control**

I. INTRODUCTION

It has long been understood that the inclusion of some series elasticity in a robotic actuation system can be beneficial for tasks involving intermittent contact and/or impact. There are many approaches for achieving desired levels of compliance, ranging from constructing low inertia actuators that are directly connected to load elements and controlled by high bandwidth control systems (often relying on force sensors to monitor load forces), to systems that explicitly incorporate compliant elements to passively manage events like impact loads. Crudely speaking, the range of approaches can be classified based on a few parameters: the stiffness of the transmission systems and physical links connecting the actuator to the end effector, the energy storage capacity of that transmission/linkage pair, and the damping ratio of the transmission/linkage. All of these parameters are directly involved in characterizing the effective impedance that the end effector presents to the environment, and thus play a critical role in how the entire robot will interact with its environment.

The property of energy storage is worth some additional attention, since it can be used to classify systems into two broad categories, those with and those without significant passive dynamics. Systems that are capable of storing an amount of energy comparable to that associated with a typical impact can be tuned such that they passively exhibit a desired behavior. Consider, for example, Raibert's original hopping machines[1]. These machines include compliant elements—air springs—capable of capturing and returning the majority of energy associated with hopping, allowing them to function with relatively minimal energy injection from a control system. This strategy follows that of animals, who store gait energy in springy tendons[2], [3], [4], [5]. More recently we have begun developing a controlled compliant actuator that we believe is capable of supporting Raibert-style running in addition to a wide variety of other locomotion and contact tasks [6], [7].

Over roughly the past decade, research centered at the MIT Leg Lab has focused on a different type of series elastic actuation. They have sought to construct series elastic actuators that have relatively small energy storage capability, but are well suited to force control applications [8]. The actuators developed at MIT utilize a very low-damping, series-spring system with a moderate level of stiffness. Specifically, the stiffness of these systems is not sufficiently soft to mimic animal-like series stiffness and the associated energy storage patterns typical for a running gait. However, in comparison to a load cell (a common "compliant" element utilized in force control applications) the devices are very soft. The MIT style series elastic actuator (MIT-SEA) is primarily intended for force control applications, and as a result of including a moderate compliance between a highly geared actuator and the load, is capable of dealing with rapidly changing force loads. In comparison to a standard gearmotor, the risk of transmission damage associated with impacts is drastically reduced.

While better suited to force control tasks involving impact than many options, the MIT-SEA introduces specific drawbacks to performance. Specifically, a poor match between actuator and load inertias can lead to load oscillations that are beyond the control bandwidth of the system, making it difficult to reliably damp high-frequency oscillations arising from impacts. The existing analysis of the MIT-SEA style actuators incorrectly assumes that robot applications will never violate these operating restrictions, making it difficult to reliably predict performance in real world applications. The applications for which the MIT-SEA is intended include both force control tasks as well as tasks involving impact, and the latter necessarily results in impulsive loads on the actuator system. When we consider that the collisions producing these loads are typically neither perfectly elastic nor perfectly in-

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elastic, we realize that understanding the dynamics presented by the actuator to the environment is critical in predicting system behavior. Furthermore, as in all robotic applications, we must consider that the load inertia is rarely constant, but rather an actuator must be designed to perform well across a wide range of load inertias, thus the system should perform well both when the load inertia is significant in comparison to the actuator's inertia, as well as in the opposite case.

The remainder of this paper is dedicated to exploring the performance capabilities and limitations of a series elastic actuator system used for a force control task in the presence of impacts. We will explore how design parameters can be adjusted to mitigate the risk of undamped oscillations, and evaluate the impact of such changes on performance. We build directly on the prior work done at the MIT Leg Lab by Robinson and colleagues[9], in an effort to better understand how best to achieve the goal of realizing reliable, safe, high-performance force actuation for general purpose robot systems.

II. BACKGROUND

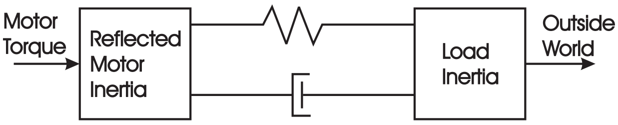

Fig. 1. A Series Elastic Actuator, with added damping. For comparison to the MIT-style SEA, the damping magnitude may be set to zero.

Classical robots tend to use gearmotors for the most rigid actuation possible, permitting good position control of the end-effector. In the control literature, "compliance" or "impedance" generally refers to behavior that is created through software control of a rigid actuator[10]. There are problems with this approach, especially for force control, high-performance or highly dynamic systems. For example, large disturbance torques on an electric motor will cause the actuator impedance to dominate the overall behavior, and a transmission will significantly worsen the effects[11]. Bandwidth limitations are caused not by controller sampling rate, but by fundamental aspects of the mechanical system[12], [13]. As a solution to some of the problems, De Schutter claims that all active force control methods require a comparable degree of passive compliance in order to yield a reasonable disturbance rejection capability[14]. In general, the more compliance in the system, the better the force control will be—for a given bandwidth limit, the force error due to unforeseen object motions is inversely proportional to 1/k, where k is the stiffness at the contact point.

Although series compliance has received recent attention in the control literature, it is one of the oldest concepts in actuation. Animals have series elasticity in most actuated joints, implemented by placing muscles in series with springy tendons. The series elasticity may be used for improved stability in a neural control system with time delay, and it is also used for gait energy storage and work amplification during walking and running gaits[15], [16]. A fishing rod is a series elastic actuator, designed to be an extremely soft spring and apply a consistent force on the hook, so the fish can't escape and the line won't break. More recent implementations of series elasticity include robot arms designed to reduce impact forces in human interaction applications[17], and constant force mechanisms which have no bandwidth limit[18].

The MIT-SEA includes a sensing and control design as well as a mechanical design[9], [8]. A spring is placed in series with a geared motor, and some load inertia is associated with the end effector, as depicted in Figure 1. A PD controller measures the deflection of the series spring, and commands motor torques so the deflection of the spring will correspond with the desired output force. The analysis is extensive, with a general mathematical model that is independent of actuator technology. Two case studies, an electromagnetic version and a hydraulic version, are compared to simulation. The bandwidth of the MIT-SEA is defined by measuring the transfer function between output force and desired force through a range of frequencies. Tests are conducted by clamping the load, and commanding positive and negative forces while measuring and recording spring position. Output impedance, which is essentially the transfer function between the output force and load position, is measured by applying a constant desired force and imposing the position of the load.

The recently demonstrated Series Damper Actuator is a conceptually similar idea to the MIT-SEA[19]. An energy dissipating device is placed in series with the motor, rather than an energy storage element as in the MIT-SEA. Oscillations do not occur, as the only energy storage elements in the system are mass inertias; any discrete change in end-effector velocity results in an instantaneous applied force by the series damper. The authors claim that the bandwidth of the system is high, and the stability is good. One major drawback to this system is that the motor must always burn energy to apply forces, spinning at a specific rate to apply a specific force.

III. THE PRIMARY ISSUE

An MIT-style series elastic actuator will apply forces effectively and operate at a high bandwidth when the load inertia is larger than the rotor inertia, and there are no motor torque limits. Electric motor torques, of course, are limited, which limits acceleration of the motor inertia and places limitations on the bandwidth of the SEA. However, the ratio of load to rotor inertias also affects the bandwidth, and can be a severe limitation in real systems. When load inertia is small compared to rotor inertia, an impulsive input at the load causes relatively high-frequency oscillation that the software controller cannot damp. The inertia of the rotor, along with the motor torque limit, prevents rapid accelerations. This limitation causes chatter during contact with a hard object, or jiggling after a bump.

On pages 105 and 106 of David Robinson's thesis[9], he states that reflected rotor inertia is hardly ever large compared to the load inertia; we contend that this assumption is generally false. For the MIT Series Elastic Actuator, the reflected inertia is 128 kg (stated on page 109). The actuated link may be less than a few kilograms for a reasonable robot arm or leg. When the end effector is in contact with the ground or a larger body, then all of the assumptions and analyses of the thesis are applicable; but before contact with the ground or during the impact, the load inertia is only that of the actuated link. Thus, robots built using the standard MIT-style SEA may be susceptible to contact chatter and other oscillation effects that cannot be corrected through software control.

This problem can be fixed in a number of different ways, or by combining different methods. Our recommended solution is to add a damper in parallel with the series spring. If designed such that the spring-damper system is critically damped for the load of the actuated link, then impacts or impulses will result in a contact without chatter. Alternatively, the rotor inertia can be reduced or the load inertia can be increased until the two values match. Because the natural oscillation frequency is the same between the motor and the load, the software controller can effectively remove energy from the system and damp unwanted oscillations. Another solution is to reduce the stiffness of the series spring. While this may reduce the likelihood of chatter on impact, it also reduces the bandwidth of the system by requiring a larger deflection for a given applied force, requiring faster acceleration by the motor, which is limited by motor torque.

The load inertia on most robot manipulators, whether they are legs or arms, is often variable during the task execution. An arm may pick up heavy objects, a leg will support the mass of the robot on the ground. This prevents a critically damped mechanical system from remaining critically damped for all tasks. However, if the load inertia becomes large compared to the rotor inertia, then series damping is no longer necessary for good performance.

IV. SIMULATION

To support our ideas that series damping can improve performance in the presence of impulses and impacts, we have simulated a series elastic actuator and subjected it to both impacts and impulses. Our simulations are based closely on those done in David Robinson's thesis work, so our simulations and his analyses can easily be compared. Our simulation uses the following closed-loop electromagnetic Series Elastic Actuator model, from page 94 of [9]:

$$F_l(s) = \frac{(K_d s + K_p)F_d(s) - (m_m s^2 + b_m s)X_l(s)}{\frac{m_m}{k_s}s^2 + \frac{b_m + k_s K_d}{k_s}s + K_p + 1}.$$

The force applied to the load by the spring, F_l, is a function of the desired force F_d and load motion X_l. The motor inertia and damping m_m and b_m, the controller stiffness and damping k_s and k_d, and the spring stiffness k_s are all derived from the physical device, and modified for various simulation cases. Only a few changes to the basic model have been made. First, the parasitic motor damping term b_m is not explicitly included. It is effectively included by combining it with the controller damping, k_d. Also, we have added a motor torque limit, which is an important realistic limitation. The system is no longer linear, and closed-form solutions are no longer feasible, so we have created all the graphs, except for the Bode plots, through simulation.

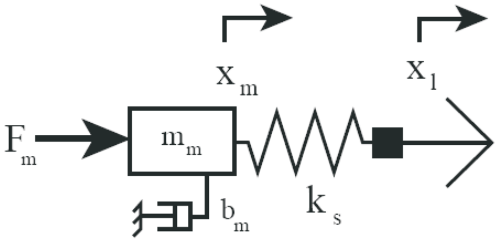

Fig. 2. The MIT Series Elastic Actuator model, copied directly from [9]

We run three different simulations. The first is a test of force bandwidth, identical to that done in [9]. The load position is clamped, and the rate at which the actuator can apply alternating positive and negative force is measured. Figure 3 shows a Bode plot obtained through simulation of the standard MIT-SEA, and also an MIT-SEA with added damping in parallel with the spring, as in Figure 1. The bandwidth of the system is slightly improved by adding series damping, and we speculate that the improvement is due to the force applied by the motor velocity. The motor can now apply force by moving at some velocity as well as by arriving at some position. This slight improvement is relatively negligible, especially in comparison to removing the series elements entirely; a standard gearmotor with no series elasticity would perform much better, because the motor need not accelerate to apply forces, and thus a motor torque limit would not limit bandwidth. This particular test illustrates the limitations of the SEA more than it illustrates any benefits.

The second and third simulations depict an impulse and an impact on the load mass of the SEA. For each of these simulations, four different cases are included:

1) SEA with torque saturation, rotor and load inertias matched
2) SEA with no torque saturation, but with a small load and a large rotor inertia
3) SEA with torque saturation, and a small load and a large rotor inertia
4) SEA with torque saturation, small load, large rotor inertia, and series damping as well as series elasticity

An impulse to the load inertia would instantaneously change the velocity. Rather than apply a discrete velocity change, we have given the load mass an initial velocity at the beginning of the simulation. The actuator is commanded

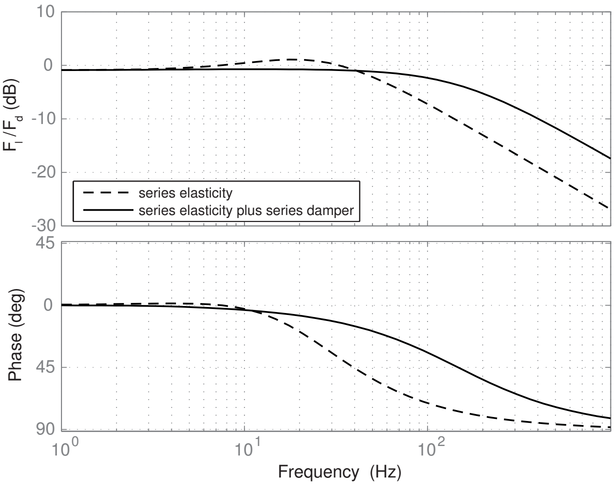

Fig. 3. Bode plot of the closed-loop transfer function of actual force on the load over the desired force, showing the actuator's force bandwidth in two cases: the standard MIT-SEA and the MIT-SEA with added series damper. The force bandwidth with the added series damper is slightly higher.

to apply zero force throughout the simulation, corresponding with zero spring deflection. The resulting graph of force applied by the series elements is shown in Figures 4 and 5. As expected, the torque-limited actuator with large rotor inertia and small load inertia oscillates significantly. By adding series damping, the oscillation is nearly eliminated. The oscillation is also greatly reduced by matching the load and rotor inertia.

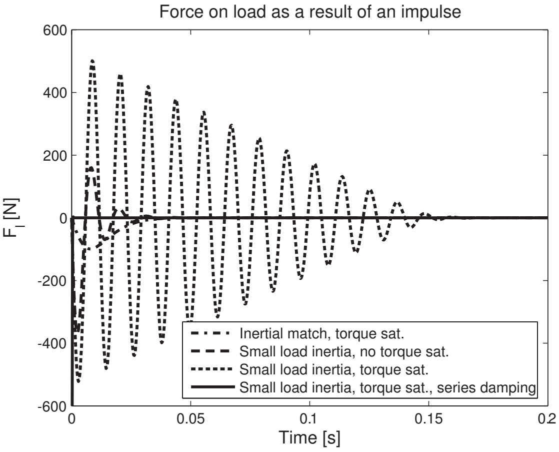

Fig. 4. Time response of the forces applied on the load by the series elements during an external impulse on the load. Only inertial matching and adding a series damper eliminates the oscillations.

An impact is modeled by adding a contact model to our simulation:

$$F_g(s) = k_g X_l(s) + b_g s X_l(s)$$

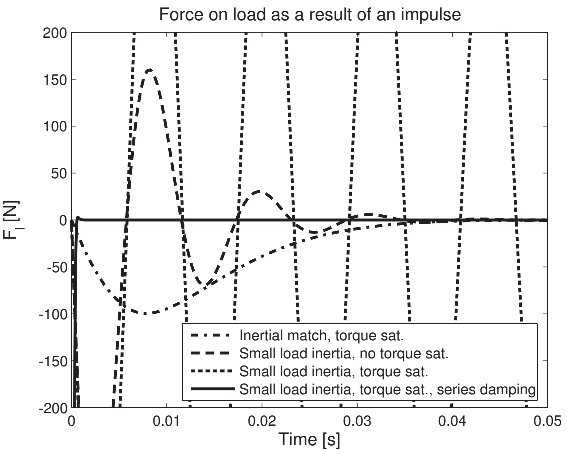

Fig. 5. A zoomed image of figure 4, more clearly showing the smaller amplitude effects.

Where F_g is the reaction force, k_g is the surface stiffness, b_g is the surface damping, and X_l is the end-effector position. F_g can only be positive, and this equation only applies force when the load mass has penetrated the ground, ($x_l > 0$). An inelastic collision would be approximated by adjusting b_g, so this system is critically damped, and an elastic collision would be approximated by setting b_g to zero. Because most collisions have some elastic component, and this elastic rebound is the cause of contact chatter, we model some small damping in the contact model so it is less than critically damped.

The MIT-SEA starts some distance away from the surface, and begins the simulation with a commanded force and an initial velocity. At some point, the load comes into contact with the wall. The load displacement is depicted in Figures 6 and 7. High-frequency oscillations result from the low-inertia load bouncing between the surface elasticity and the MIT-SEA elasticity, and a low-frequency oscillation exists in case of the higher load inertia. Only with a series damping element is this oscillation eliminated.

Forces in the series elements resulting from contact are depicted in Figures 8 and 9. All cases settle on the commanded force eventually, but it does take the case of the higher load inertia about twenty times as long.

V. DISCUSSION AND CONCLUSIONS

Depending on the task at hand, adding series compliance can either help or harm the performance. But in the right application and with the right implementation, series compliance is a major benefit. The MITSEA analysis and implementation is extensive and informative, and as long as all of the

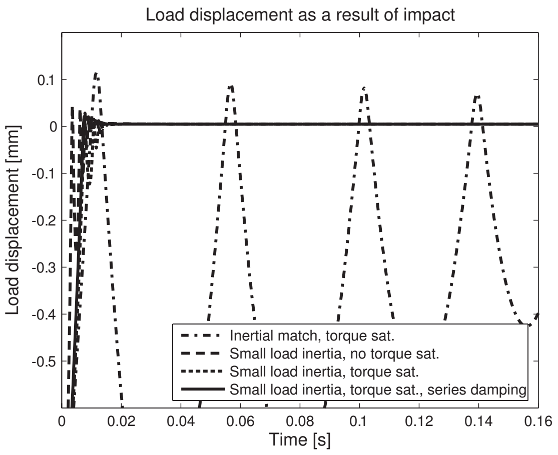

Fig. 6. Displacement of the load during an impact with a semi-elastic surface, starting a certain distance away from the surface, given an initial velocity and a command of $500N$ force. In three cases contact with the surface causes chatter, where the contact is broken and reestablished several times before settling. Only in the case of an added series damper does the load settle without chatter. Although this figure shows relatively small velocities and displacements for visibility reasons, similar effects occur at higher speeds.

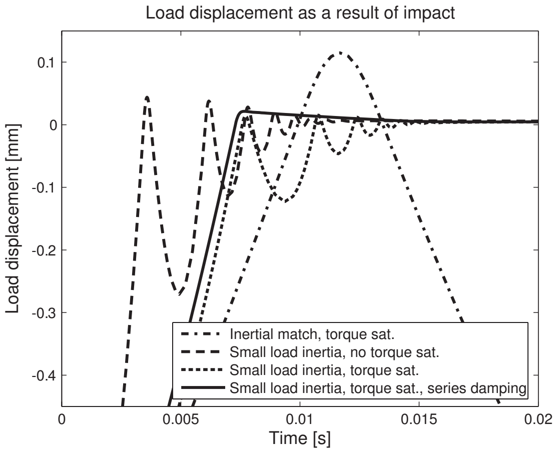

Fig. 7. A zoomed image of Figure 6, clearly showing the high-frequency chatter of the non-damped systems, and the fast settle time of the damped system.

assumptions are met, the analyses are accurate. However, the assumptions are not met in many practical applications; the most difficult problem is low load inertia paired with high rotor inertia. By adding series damping, the control authority over the system at all bandwidths is improved. Ideally, the series elements should include a spring and a damper such that the lowest expected load will be critically damped. By eliminating unwanted oscillation through series damping or other methods, series elasticity is an effective actuator technology for force-control applications in which unexpected impacts or fast disturbances are regularly encountered.

An interesting difference between a standard MIT-SEA and one with added damping is that the series damper relates the spring's velocity to applied load force as well as the spring's position. The software controller can take advantage of this additional coupling, and apply the desired force through a combination of velocity and position. This is the most likely explanation for the improved bandwidth on the SEA with series damping.

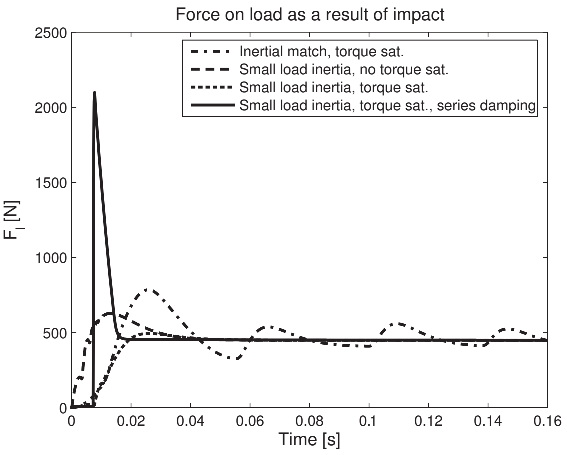

Fig. 8. Forces applied to the load by the series elements in case of an impact. In all cases there is an overshoot of force due to the impact. Eventually all cases settle at the commanded $500N$ force, the case with series damper settles first and the case with large load inertia last.

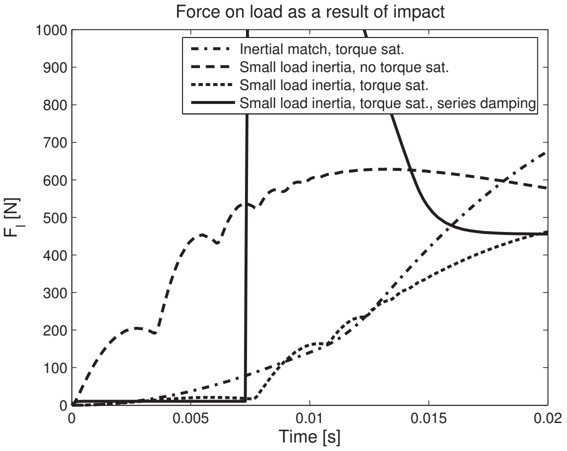

Fig. 9. A zoomed image of Figure 8. The force fluctuations due to contact oscillation are more clear in this image, where the lines wiggle.

The additional damping also causes a force spike at the beginning of an impact. This force spike is presumably much lower than that seen by a gearmotor on impact, but it is higher than a standard MIT-SEA. Depending on the application, this may or may not be acceptable. Perhaps the damping ratio could be proportional to the spring deflection, to avoid the initial spike in force, but still damp out the oscillations. We will consider this as well as more sophisticated controllers in future work.

This paper describes ideas that are supported by simulation, but experiments on hardware would be much more convincing. We may perform hardware experiments in the near future using existing haptic devices in the Biorobotics lab at Delft

University. In the intermediate future, we will build a device, perform hardware experiments, and incorporate in a force-control robotics application.

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REFERENCES

[1] Marc Raibert. *Legged Robots That Balance*. MIT Press, Cambridge, Mass., 1986.

[2] Giovanni A. Cavagna. Elastic bounce of the body. *Journal of Applied Physiology*, 29(3):279–282, 1970.

[3] Robert J. Full and Claire T. Farley. Musculoskeletal dynamics in rhythmic systems - a comparative approach to legged locomotion. In J. M. Winters and P. E. Crago, editors, *Biomechanics and Neural Control of Posture and Movement*. Springer-Verlag, New York, 2000.

[4] R. McN. Alexander. Three uses for springs in legged locomotion. *The International Journal of Robotics Research*, 9(2):53–61, April 1990.

[5] T. A. McMahon. The role of compliance in mammalian running gaits. *Journal of Experimental Biology*, 115:263–282, 1985.

[6] Jonathan W. Hurst and Alfred A. Rizzi. Physically variable compliance in running. In *International Conference on Climbing and Walking Robots*. Springer-Verlag, 2004.

[7] Jonathan W Hurst, Joel E Chestnutt, and Alfred A Rizzi. An actuator with physically adjustable compliance for highly dynamic legged locomotion. In *IEEE International Conference on Robotics and Automation*, 2004. (to appear).

[8] Gill A. Pratt and Matthew M. Williamson. Series elastic actuators. In *IEEE International Conference on Intelligent Robots and Systems*, volume 1, pages 399–406, 1995.

[9] David William Robinson. *Design and Analysis of Series Elasticity in Closed-Loop Actuator Force Control*. PhD thesis, Massachusetts Institute of Technology, June 2000.

[10] Miomir Vukobratovic and Atanasko Tuneski. Contact control concepts in manipulation robotics — an overview. In *IEEE Transactions on Industrial Electronics*, volume 41, February 1994.

[11] Dale A. Lawrence. Actuator limitations on achievable manipulator impedance. In *IEEE International Conference on Robotics and Automation*, pages 560–565, 1989.

[12] Steven D. Eppinger and Warren P. Seering. Understanding bandwidth limitations in robot force control. In *IEEE International Conference on Robotics and Automation*, pages 904–909, 1987.

[13] Steven D. Eppinger and Warren P. Seering. Three dynamic problems in robot force control. In *IEEE Transactions on Robotics and Automation*, volume 8, December 1992.

[14] J. De Schutter. A study of active compliant motion control methods for rigid manipulators based on a generic control scheme. In *Proceedings of the IEEE International Conference on Robotics and Automation*, pages 1060–1065, 1987.

[15] Thomas J. Roberts. The integrated function of muscles and tendons during locomotion. *Comparative Biochemistry and Physiology part A*, pages 1087–1099, 2002.

[16] Thomas J. Roberts, Richard L. Marsh, Peter G. Weyand, and C. Richard Taylor. Muscular force in running turkeys: The economy of minimizing work. *Science Magazine*, 275, February 1997.

[17] Antonio Bicci and Giovanni Tonietti. Fast and "soft-arm" tactics. *IEEE Robotics & Automation Magazine*, 2004.

[18] Dhiraj R. Nahar and Thomas Sugar. Compliant constant-force mechanism with a variable output for micro/macro applications. In *Proceedings of the 2003 IEEE International Conference on Robotics and Automation*, 2003.

[19] Chee-Meng Chew, Goek-Soon Hong, and Wei Zhou. Series damper actuator: A novel force/torque control actuator. *Humanoids*, 2004.