2014 5th IEEE RAS & EMBS International Conference on
Biomedical Robotics and Biomechatronics (BioRob)
August 12-15, 2014. São Paulo, Brazil

ServoSEA Concept: Cheap, Miniature Series-Elastic Actuators for Orthotic, Prosthetic and Robotic Hands

Serdar Ates[1], Victor I. Sluiter[1], Piet Lammertse[2] and Arno H.A. Stienen[1,3]

Abstract— **For interactive humanoids, rehabilitation robots, and orthotic and prosthetic devices, the human-robot interaction is an essential but challenging element. Compliant Series-Elastic Actuators (SEAs) are ideal to power such devices due to their low impedance and smoothness of generated forces. In this paper we present the ServoSEA, which is a miniature Series-Elastic Actuator (SEA) based on cheap RC servos, and which is useful for actuation of orthotic, prosthetic or robotic hands. RC servos are complete packages that come with rotary motor and sensor and have an integrated control board to control the output angle. In the ServoSEA, a small rotational spring is attached to the output shaft and the internal rotary sensor is relocated to measure the spring deflection. These small modifications immediately make the integrated control board behave as a series-elastic torque controller. Here we present several design alternatives and report on the performance of our implementation that will be used in the active SCRIPT wrist and hand orthosis. The performance measurements showed that feedforward control of the example implementation of the ServoSEA results in acceptable, though not perfect, force tracking behavior. It is clear that although the ServoSEA concept is universal, final performance strongly depends on the quality of the original RC servo.**

I. INTRODUCTION

In recent years, hand therapy with robotic tools have seen a surge in attention [1]. Devices such as MIT-MANUS hand module [2], RiceWrist-S [3], and the UT Wrist-Exoskeleton [4] are promising implementations of active orthoses for rehabilitation therapy. In these, interaction between human and robot has to be carefully controlled to balance the needs for assistance with those for therapy. Dexterous actuators are essential for this purpose. For home therapy, as the goal in SCRIPT project (EU-FP7-ICT-2011-7, 288698), these actuators have to be affordable too.

Series elastic actuators (SEA) have an elastic element in series with an actuator, most often respectively a spring and an electro motor. SEAs have many advantages such as shock tolerance, low impedance, and low friction that can provide high quality force delivery in active orthoses. SEAs are also robust, affordable and stable, thanks to their compliant elastic element instead of delicate, expensive, chatter-inducer load cell in SEA's. Smoothness of gear reduction (which affects the torque profile drastically) is not critical anymore, and they react like a compliant instead of stiff spring at higher frequencies. All these abilities make SEA's ideal for exoskeletons, active orthoses, haptic interfaces, and other wearable robots [5], [6], [7], [8], [9], [10]. The major drawback of SEA is that correcting for small force changes requires many small changes of the spring deflection and thus the servo motor angle, which can significantly lower the life expectancy of the motors.

Supporting grants: SCRIPT (FP7, 288698), VENI Stienen (STW, 12479).
[1]Biomechanical Engineering, University of Twente, Enschede (NL).
[2]Robotics Division, Moog, Nieuw-Vennep (NL).
[3]Physical Therapy and Human Movement Sciences, Northwestern University, Chicago (IL, USA).
We wish to thank Israel Mora-Moreno, Arvid Keemink and Joan Lobo-Prat for advice and assistance during the development.
Corresponding author: Arno Stienen (arnostienen@gmail.com).

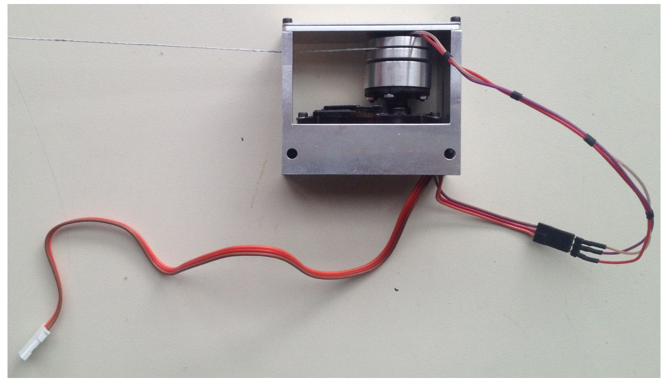

Fig. 1. *Example of the ServoSEA concept that creates a miniature series-elastic actuator by making small modifications to a cheap, conventional RC servo.*

In a hand orthosis, the alternative to SEA—direct actuation without an elastic element in series—would leave just the actuator to generate smooth, adaptable interaction forces. This would require either a direct-drive actuator or a high-power actuator, which are both too heavy to use. And most light-weight and affordable actuators, such as the often used Firgelli L12/L16 actuators (Firgelli Technologies Inc., Victoria BC, Canada), are not fast enough to keep up with the voluntary movements of the user. With such an actuator, the movement characteristics of the hand in the orthosis are completely dominated by high reflected inertia of the actuator. The resulting restricted movement freedom has a detrimental effect on the therapy efficacy, as the human would quickly learn that his own muscle activation patterns have only limited influence on the movement.

A second alternative to SEA—parallel placement of the passive and active elements—does not result in realistic concepts that can be used in an active orthosis. In such a configuration, the primary function of the spring becomes to assist the actuator in the generation of power. A weak spring will contribute relatively little to the total force generated. A strong spring will be of most use when desiring a force response relatively close to the spring characteristics, but will need to be counteracted by a strong actuator response when

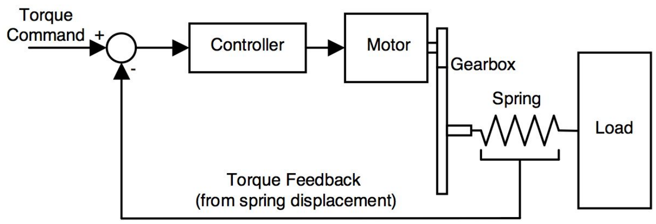

Fig. 2. *Control scheme from [5] of a SEA, in which the deflection of an elastic element (spring), and thus the output torque applied to the load, is controlled with an actuator (motor).*

deviating from this, thus counteracting the beneficial effect of the spring parallel to the actuator. In a parallel configuration, the dynamics performance will be limited primarily by power available in the actuator, as it either has to do all the work (weak spring) or do a lot of work to keep the force response either constant (strong, stiff spring) or at multiple desired levels (strong, slack spring). For the wrist and finger orthosis in the SCRIPT project, it is almost impossible to find a combination of spring and actuator that could work in a parallel configuration.

This report details the exploratory work performed to investigate performance characteristics of the ServoSEA (see Fig. 1, which is a miniature Series-Elastic Actuator (SEA) based on cheap RC servos. With the ServoSEA, we have integrated active and passive actuation elements into a safe semi-active actuator for the upcoming SCRIPT Active Orthosis.

II. Design

The ServoSEAs needed for the SCRIPT Active Orthosis need to power the fingers, thumb and wrist in extension only, as many individuals after stroke need this to overcome the characteristic hyperflexion in the hand. Therefore, a unidirectional design using tension cables is used. For the fingers and thumb, an extension torque of 0.4 Nm was selected as the desired compromise between safety and enabling function. For the wrist, this is 2.0 Nm. These requirements are similar to those provided by the passive leaf springs and tension cords in the SCRIPT Passive Orthosis, and the reasoning behind them can be found in [11].

A. Hardware

At its simplest description, the SEA is spring in series with an actuator. With the ServoSEA power eventually transmitted thought a cable to the joints, valid combinations of spring and servo motor include:

- Linear servo, linear spring, with no cable drum needed.
- Rotational servo, cable drum, linear spring.
- Rotational servo, rotational spring, cable drum.

Although the cable to the joints can be directly connected to the spring with the linear-linear combination, measuring the spring deflection requires a linear distance sensor. These require more space and are heavier, more delicate and more expensive than a conventional rotational potentiometer. Using a rotational spring allowed the usage of rotational

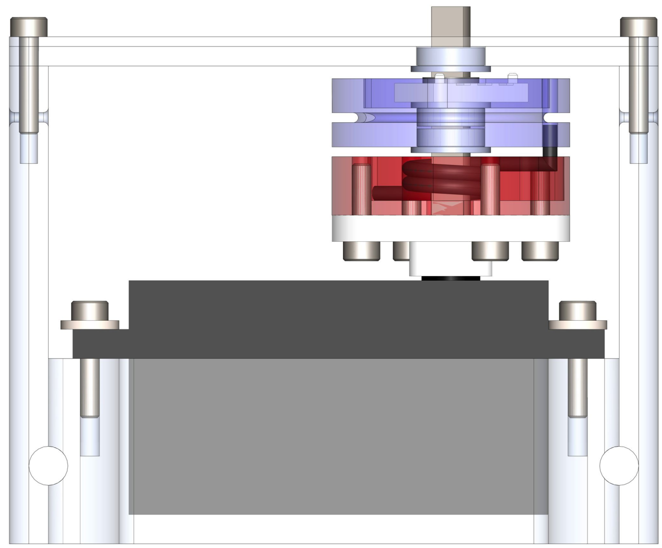

Fig. 3. *The side view of the ServoSEA that shows the location of the spring and potentiometer relative to the drums. For labeling of components, see Fig. 4. Note the compact design with the potentiometer and spring integrated into the drums, in combination with the BMS-705MG Low Profile High Torque Servo. The cable connecting the external potentiometer to the servo housing can be seen in Fig. 1.*

potentiometers and was therefore the preferred option for the ServoSEA.

For the SCRIPT Active Orthosis, we need a combination of elastic elements, actuators and sensors that are light weight, reliable and cheap. Radio controlled (RC) model cars and airplanes have the same requirements, and the technologies developed there provided us with valuable inspiration. For control of steering, ailerons and flaps, the RC models use small servo motors consisting of an electric motor, a gear train, and servo-loop controller. This servo loop controller has a rotary position sensor—generally a potentiometer—on the output axis of the servo that is used to control output position through a tuned closed-loop controller.

These RC servos are therefore complete packages for closed-loop position control. In the ServoSEA, we have attached the aforementioned rotational spring to the output shaft, and we relocated the internal rotary sensor to measure the spring deflection. The input signal which was originally used to control the output position of the servo can now be used to control the spring deflection and thus the output torque (see Fig. 2). These small modifications have converted the position-controlled RC servo into the torque-controlled ServoSEA that needs no other circuitry than the integrated control board.

The side view of the ServoSEA in Fig. 3 shows the location of the spring and potentiometer relative to the drums. Note the compact design with the potentiometer and spring integrated into the drums, in combination with the BMS-705MG Low Profile High Torque Servo.

The exploded view in Fig. 4 shows the order of components in the ServoSEA. Here, the d-shaped axis, spring drum and servo disk are firmly connected and rotate as one, powered by the BMS-705MG Low Profile High Torque

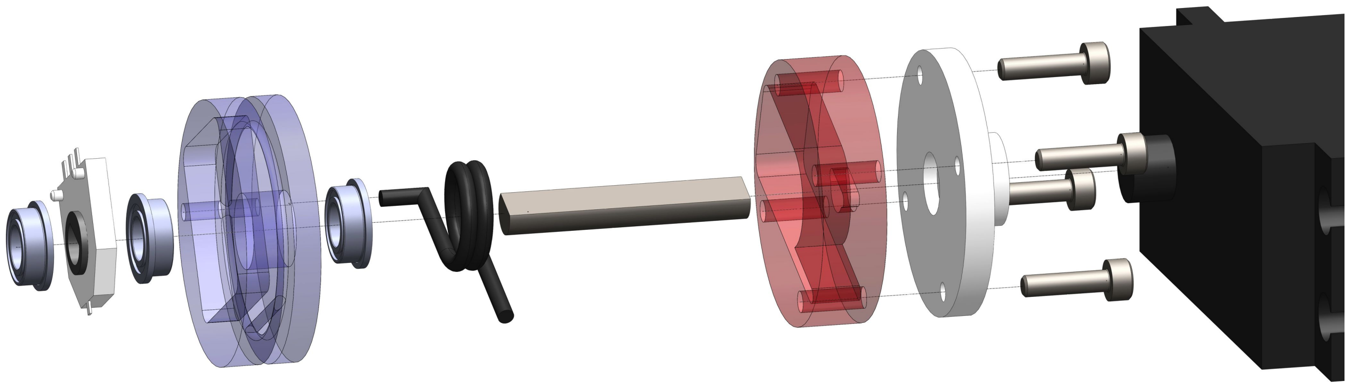

Fig. 4. *The exploded view of the ServoSEA. From left to right: ball bearing, potentiometer (white), ball bearing, cable drum (blue), ball bearing, spring (black), d-shaped axis, spring drum (red), servo disk (white), bolts, servo (black). The d-shaped axis, spring drum and servo disk are firmly connected and rotate as one. The cable drum can rotate while deflecting the spring, with the relative rotation between the drums measured by the potentiometer. The drums are strongest when machined from aluminum, but can potentially be 3D printed too.*

Servo with Metal Gears (purchased from HobbyKing). The cable drum can rotate while deflecting the spring, with the relative rotation between the drums measured by the potentiometer (Bourns 3382H). The drums are strongest when machined from aluminum, but can potentially be 3D printed too. However, in that case, the maximum allowable torques will be lower. Also, by varying the diameter of the cable drum, additional gearing effects can be achieved.

For the ServoSEA, it is irrelevant if the power transmission is trough cables, gearings, push-pull rods, parallelograms, or any other means. However, using a one-directional cable being wound over a cable drum has the added advantage that a much large actuated movement range can be used, as the cable can be wound many times over the drum. This does require to remove the mechanical endpoint stops if present in the RC servo to make it continuous: after the gear train is disassembled the mechanical blocking notch can be removed.

The modified RC servo can be seen in Fig. 5. From the servo housing, now two cables protrude: the regular power/signal wire, and the newly added potentiometer wire that connects to the external potentiometer. The external potentiometer replaces the internal one and is soldiered directly onto the control board in its place.

B. Control

The ServoSEA is controlled using the control scheme in Fig.2. To set the desired output force, the desired potentiometer deflection—which is the output force divided by the known spring stiffness—is given to the internal controller of the servo motor via adjustable set points. Therefore, no external control loop is needed and a much simpler external set-point generator can control the output torque of the ServoSEA.

Most servo motors use three wires for power (two) and control (one), with a constant supply voltage over the power wires and a PWM-signal between 0-100% controlling the desired position. In the ServoSEA, this PWM signal is now directly correlated with the desired spring deflection, and thus with the desired output torque. For a selected output torque, the control board tries to maintain the required spring deflection. When the user performs voluntary movement, the resulting change in spring extension is measured by the potentiometer. The servo controller then rotates the spring drum until the spring deflection is back at the desired (dynamic) set point.

III. Simulation

The performance of the SEA depends on the spring strength and stiffness and the actuator power, speed and torque. For our application, the required torque is independent of the chosen components. That means that for a given configuration, the required spring strength stays constant and the springs stiffness becomes the selectable parameter. Similarly, many RC servo motors have comparable maximum output speeds, with large difference in the available output torque. As power is speed times torque, with constant maximum speeds the output torque relates closely with the output power. We have chosen to use servo motor torque as the selectable parameter. More torque results in a higher maximum output force in the cable, and—more importantly—more torque allows the servo motor to accelerate quicker to the desired velocity. This increasing the performance bandwidth.

We have simulated the ServoSEA with a stiff spring (2.0 Nm/rad) and a strong, generic servo motor (3.0 Nm). In the simulations, we have perturbed the ServoSEA with a voluntary rotation of the human wrist based on the minimum jerk trajectory principle over a range of $\pm 30°$. Such a movement has a constant acceleration, a bell shaped velocity profile, and a sigmoid displacement from the start to the final position. To reflect both flexion and extension movement, the simulated wrist goes from neutral (0°) via max flexion (30°) to max extension (-30°), followed by the reverse of these movements. These movements are completed in four seconds and reflects performance expected by a relatively mildly-affected individual after stroke. (Note that such a profile would result in a highly variable interaction force profile in the SCRIPT Passive Orthosis [11].) Fig. 6 details

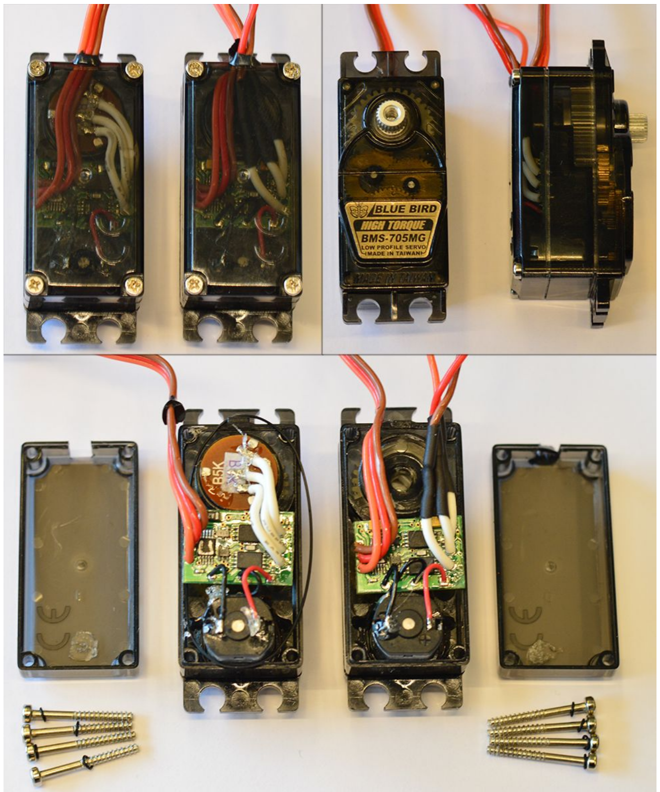

Fig. 5. *Three views of the original (left) and modified (right) RC servo, side by side. In the bottom figure, the original servo has its three white wires connected to the internal potentiometer. In the modified servo, we have removed that potentiometer and soldered an external connector to the three white wires, that connects to the external potentiometer. In the top left, the cables can be seen underneath the see-through housing. In the top-right, top and side views of the servo motor.*

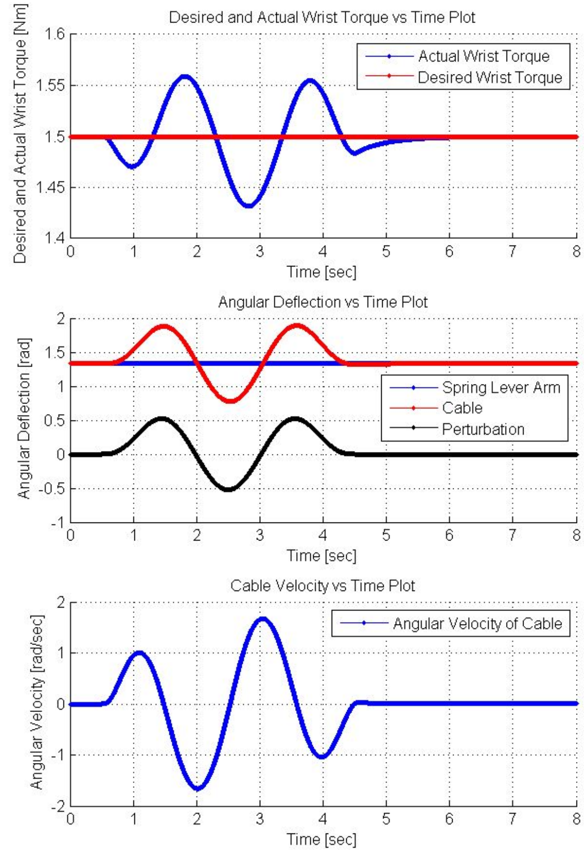

Fig. 6. *Simulation of wrist ServoSEA keeping the applied torque constant despite being perturbed by a voluntary rotation of $\pm$0.5 rad, with a 2 Nm/rad spring and a powerful 3.0 Nm servo. Note that despite the fast perturbation speed of 1 rad/s, the output torque does not deviate more that 4% from the desired torque.*

the results of that simulation. Despite the large and relatively fast movement deviations, the output torque does not deviate more that 4% from the desired torque.

IV. Performance

To determine the dynamic performance of the ServoSEA, we build a test setup around a ServoSEA suitable for actuating the fingers (see Fig. 7). We choice to demonstrate performance for the finger, as precision for smaller loads is more difficult to achieve than when using the large servos for the wrist.

In the test setup, we used the BMS-705MG servo that has a reported maximum torque of 0.6 Nm and speed of 0 to 60° in 0.18 s, in combination with a spring with a stiffness of 0.91 Nm/rad, a maximum deflection angle of 30°, and a maximum torque of 0.397 Nm.

The setup consists of a square frame with a Futek LSB200 (111 N) force sensor hanging from the top. The bottom of the sensor is attached to the ServoSEA, which is clammed to the bottom of the frame. The servo motor is controlled through PWM from an Arduino Due, which also measures the amplified force sensor signal with its 12bit ADC. The Arduino is programmed to generate the desired PWM signals and transfers its recorded ADC signals in real-time to the connected Windows PC, where these signals are saved to text file.

In the RC servos, a pulse width of 0.5 ms in a 20 ms period puts the output angle at -90° deflection, which is at the mechanical minimum limit of most servos. 1.5 ms puts the angle at 0° (neutral), and 2.5 ms at the mechaninical maximum limit of +90°. Thus 1 ms of pulse in a 20 ms period, relates to 90° of deflection.

In the force tracking bandwidth, we used sinusoidal inputs between 1.4 (45% of maximum range) and 1.6 ms (55% of maximum range) for the pulse-widths, thus roughly equaling 18° of deflection, with 1.4 ms causing more spring deflecting and higher output forces than 1.6 ms. To determine the bandwidth, we tracked these sinusoidal inputs with frequencies of 0.1, 0.2, 0.5, 1, 2, 5, 10 and 20 Hz.

In the step response experiments, the steps were from 1.6 to 1.55, 1.5, and 1.45 ms, roughly equaling intended steps of 4.5, 9, and 13.5°, respectively. Output forces were converted to ServoSEA torques by multiplying the measured force times the drum radius of 9 mm.

The results show that simple feed-forward control results

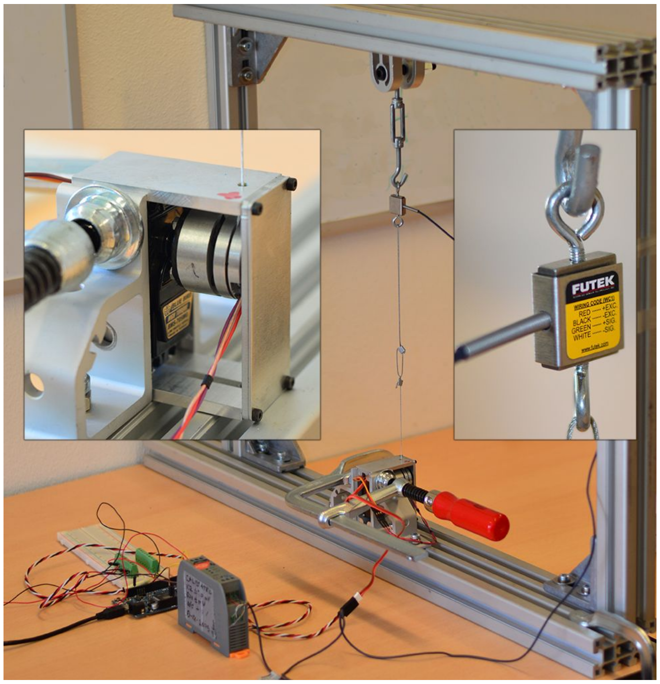

Fig. 7. *Test setup to measure the dynamic performance of the ServoSEA. A force sensor (top of frame, insert top-right) is hung from a frame and pulled on from the bottom by the ServoSEA (bottom of frame, insert top-left). Also visible are the Arduino Due and the ICP DAS SG-3016-G-CR Strain Gage Module (bottom left).*

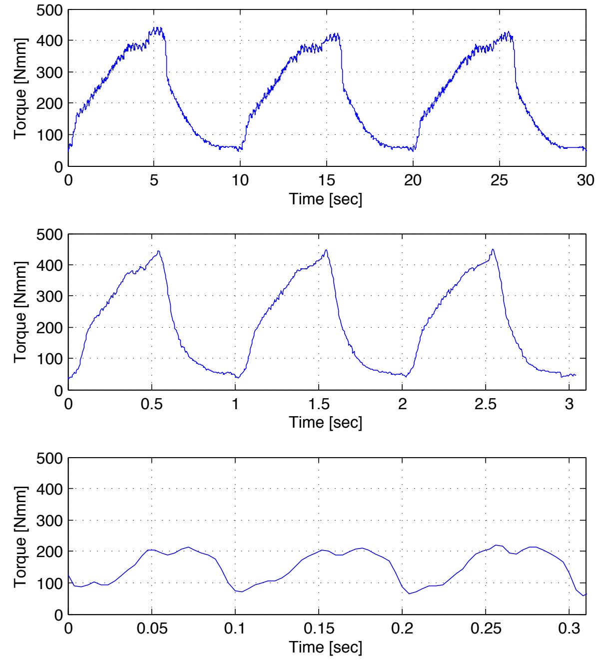

Fig. 8. *Measured force tracking at 0.1 (top), 1 (middle) and 10 Hz (bottom), with PWM signal between 45% and 55% of maximum PWM. This results in a roughly sinusoidal-shaped torque between 0.05 and 0.45 Nm at 0.1 and 1 Hz, and between 0.05 and 0.22 Nm at 10Hz.*

in acceptable—though far from perfect—force tracking behavior of the ServoSEA (see Fig. 8 for the 0.1, 1 and 10 Hz sines). For 0.1 and 1.0 Hz sines, the output ranges between 0.05 and 0.45 Nm. For a 10 Hz sine, it is reduced to 0.05 to 0.22 Nm. In the related bode plot (Fig. 9), the bandwidth can be estimated to be at around 4 Hz.

In the steps responses, the ServoSEA is able to realize these with slopes of about 1.75 Nm/s and without overshoot (see Fig. 10). All force traces where filtered using a zero-lag, dubble-pass butterworth filter (first order, 50 Hz).

V. Discussion

With SEA, the achieved performance depends strongly on the choice of actuator bandwidth and spring stiffness. A slack spring will make the SEA more compliant for small endpoint deviations and motor errors, but will also strongly limit the force bandwidth. A stiff spring has the opposite effects. With a powerful actuator, this force can be achieved with high output velocities and thus much higher output bandwidth. But a powerful actuator is also heavy and large.

Safety can be assured with the help of either electronic, software and mechanical mechanisms or their combinations. The elastic element in series increases the safety since it reacts like a spring at high frequencies which makes SEA robust and shock-tolerant against perturbations with a smooth response.

Comfort is an outcome of the force profile required by the active orthosis and is strongly related to the control strategies. Chattering in the force provided by the active orthosis introduces discomfort at the wrist or fingers. In order to make patients feel in a more non-impeding natural way, a smooth assistive force should be provided by the active orthosis.

Control criteria is directly affected by complexity of control strategies. In our simulations, conventional PID controllers which are well-known and easy-to-implement performed acceptably. In case of need, different control strategies for robust control may be investigated upon completion of fully functional and operational prototypes. This is dependent on the feedback provided by the clinical partners.

Force-tracking performance still needs to be optimized. Currently, residual friction between drums and springs and noise from the PWM-carrying wires, reduce the achieved performance.

SEA requires more motor displacements to keep the spring deflection at the desired value, and may therefore use more energy through the continuous accelerations and decelerations. Furthermore, not all types of RC servos are suitable for continues use close to the maximum torque as the ones with plastic casings will have trouble dissipating the heat they generate. During testing, we overheated several servos and found the ones using brushless technology and metal casings as heatsinks to perform significantly better.

The control board modification can be made within an hour. Almost all RC servo motors have similar standard configuration, which means in case of use other type of RC servo motors it would not differ drastically to modify. It does not introduce any failure or malfunctioning electrically since we only extend potentiometer electrical connections and do not intervene the electronics. But, re-assembling of

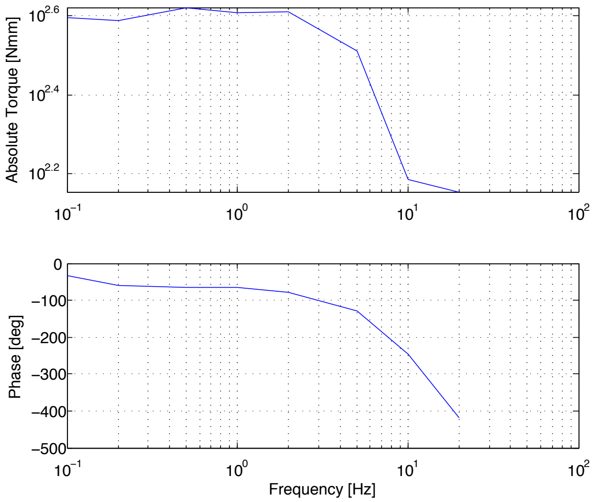

Fig. 9. *Bode plot estimated from force tracking measurements at 0.1, 0.2, 0.5, 1, 2, 5, 10 and 20 Hz. The bandwidth of the ServoSEA is estimated to be at around 4 Hz.*

the mechanical parts such as gear train, screws and housing, after mechanical modification should be done very carefully to avoid further mechanical failures or malfunctioning.

Note that the achieved performance strongly depends on the strength and quality of the RC servo that was modified to achieve ServoSEA. A better RC servo or better potentiometer will results in a better performance. For instance, we have noticed that performance of cheap RC servos that can be bought for around \$15 (such as the one used in the evaluations: BMS-705MG) has a continues torque that is less than 20% of the reported maximum torque, especially at frequencies above 5 Hz. Thus although the ServoSEA concept is universal, performance strongly depends on the quality of the original RC servo.

VI. Conclusion

Human-robot interaction is an essential but challenging element for interactive humanoids, rehabilitation robots, and orthotic and prosthetic devices. We present the ServoSEA concept as a potential alternative solution to actuate these decives. ServoSEA is a miniature Series-Elastic Actuator (SEA) based on cheap RC servos that can be used for actuation of orthotic, prosthetic or robotic hands.

In the ServoSEA, a small rotational spring is attached to the output shaft of the RC servo and the internal rotary sensor is relocated to measure the resulting spring deflection. These small modifications immediately make the integrated control board behave as a series-elastic torque controller, without the need for complex electronics or additional control software.

Simulation results show that the optimal combination is a fast servo motor with slack spring. It is reasonable since slack spring reflects SEA as a pure spring element against perturbations and fast servo motor provides the required torque quickly.

The performance measurements showed that feedforward control of the ServoSEA results in acceptable, though not perfect, force tracking behavior. It should be noted that although the ServoSEA concept is universal, performance strongly depends on the quality of the original RC servo.

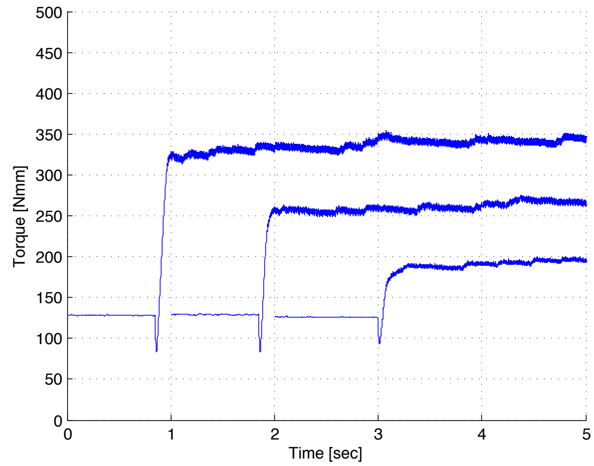

Fig. 10. *Measured step responses from 55% to 52.5% (top), 55% to 50% (middle) and 55% to 47.5% of maximum PWM (bottom), resulting in a steps from 0.13 to 0.19 Nm, 0.26 Nm and 0.32 Nm, respectively.*

References

[1] S. Balasubramanian, J. Klein, and E. Burdet, "Robot-assisted rehabilitation of hand function," *Current opinion in neurology*, vol. 23, no. 6, p. 661, 2010.

[2] H. I. Krebs, B. T. Volpe, D. Williams, J. Celestino, S. K. Charles, D. Lynch, and N. Hogan, "Robot-aided neurorehabilitation: a robot for wrist rehabilitation," *Neural Systems and Rehabilitation Engineering, IEEE Transactions on*, vol. 15, no. 3, pp. 327–335, 2007.

[3] A. U. Pehlivan, S. Lee, and M. K. O'Malley, "Mechanical design of ricewrist-s: A forearm-wrist exoskeleton for stroke and spinal cord injury rehabilitation," in *Biomedical Robotics and Biomechatronics (BioRob), 2012 4th IEEE RAS & EMBS International Conference on*, pp. 1573–1578, IEEE, 2012.

[4] J. H. Beekhuis, A. J. Westerveld, H. van der Kooij, and A. H. Stienen, "Design of a self-aligning 3-dof actuated exoskeleton for diagnosis and training of wrist and forearm after stroke," in *International Conference on Rehabilitation Robotics (ICORR)*, IEEE, 2013.

[5] G. Wyeth, "Control issues for velocity sourced series elastic actuators," in *Proceedings of the Australasian Conference on Robotics and Automation 2006*, Australian Robotics and Automation Association Inc, 2006.

[6] G. A. Pratt and M. M. Williamson, "Series elastic actuators," in *Intelligent Robots and Systems 95.'Human Robot Interaction and Cooperative Robots', Proceedings. 1995 IEEE/RSJ International Conference on*, vol. 1, pp. 399–406, IEEE, 1995.

[7] N. G. Tsagarakis, I. Sardellitti, and D. G. Caldwell, "A new variable stiffness actuator (compact-vsa): Design and modelling," in *Intelligent Robots and Systems (IROS), 2011 IEEE/RSJ International Conference on*, pp. 378–383, IEEE, 2011.

[8] D. W. Robinson, J. E. Pratt, D. J. Paluska, and G. A. Pratt, "Series elastic actuator development for a biomimetic walking robot," in *Advanced Intelligent Mechatronics, 1999. Proceedings. 1999 IEEE/ASME International Conference on*, pp. 561–568, IEEE, 1999.

[9] G. Mathijssen, P. Cherelle, D. Lefeber, and B. Vanderborght, "Concept of a series-parallel elastic actuator for a powered transtibial prosthesis," *Actuators*, vol. 2, no. 3, pp. 59–73, 2013.

[10] R. v. Ham, T. Sugar, B. Vanderborght, K. Hollander, and D. Lefeber, "Compliant actuator designs," *Robotics & Automation Magazine, IEEE*, vol. 16, no. 3, pp. 81–94, 2009.

[11] S. Ates, J. Lobo-Prat, P. Lammertse, H. van der Kooij, and A. H. A. Stienen, "Script passive orthosis: Design and technical evaluation of the wrist and hand orthosis for rehabilitation training at home," in *International Conference on Rehabilitation Robotics (ICORR)*, IEEE, 2013.