2014 IEEE International Conference on Robotics & Automation (ICRA)
Hong Kong Convention and Exhibition Center
May 31 - June 7, 2014. Hong Kong, China

A Mechanically Adjustable Stiffness Actuator(MASA) of a robot for knee rehabilitation

Jaewook Oh, Soojun Lee, Myotaeg Lim, and Junho Choi

Abstract— **This paper presents a Mechanically Adjustable Stiffness Actuator(MASA) for knee rehabilitation of stroke patients. The MASA is designed for safer and more effective physical human-robot interaction with patients in rehabilitation. The MASA consists of cantilever springs, a double-tripod parallel mechanism, and a torque limiter. Using the double-tripod parallel mechanism and two identical actuators, the effective length and the resting position of the cantilever springs are controlled independently. Changes of the effective length of the cantilever springs result in variation of the stiffness of the MASA. One end of each cantilever springs is attached to an axis via the torque limiter. When an external torque beyond the preset threshold is applied from and to the axis, the torque limiter is released so the axis rotates freely regardless of the position of the actuators. The MASA is used for a knee rehabilitation robot. Due to the springs and the torque limiter, physical safety of the patients is guaranteed in case of unexpected involuntary muscle activities (i.e. spasticity) during a therapy session. With changing stiffness of the MASA, the amount of assistance by the robot is possible to be adjusted.**

I. INTRODUCTION

For better rehabilitation of stroke patients, repetitive muscle exercises with high intensity are required. During a typical therapy session, intensity of the exercises is limited due to lack of availability of therapists. It is a appropriate application of robots since robots are suitable for repetitive and intensive work. However, physical safety is one of the problems caused by use of robots, which needs to be addressed before introducing the robots into the therapy session. In this paper, a mechanically adjustable stiffness actuator(MASA) is presented. The MASA is developed for rehabilitation of a knee joint of stroke patients.

Since high compliance requires high gain in active compliance control, which leads to instability of the system, for safer and more effective physical human-robot interactions, wearable robots with passive compliance have been studied by many researchers. In [1], a series elastic actuator was introduced and analyzed, which was adopted in an exoskeleton for load-carrying augmentation due to its bandwidth for force control in [2]. Kwa *et al.* developed an exoskeleton with joints with passive compliance to assist patients to walk. The exoskeleton used Rotary Series Elastic Acuators(RSEA's) in [3].

In addition to enhancing human power, exoskeleton robots with compliance are used in rehabilitation of patients. A robotic exoskeleton for gait rehabilitation using series elastic actuators was developed and discussed in [4] and [5]. Because of the spring used in the actuators, a force control problem became a position control problem and the actuator had better resistance in case of impact.

In [6], benefits and limitations of series elastic actuators were discussed, among which stiffness limitation was included. It leads to studies on joints with variable stiffness by many researchers. In [7], force of springs, which pressed rollers against cam disk, was changed to realize stiffness variation of the actuator. The designed variable stiffness joint was used to actuate a 4-DOF manipulator. In [8], leaf springs were used to generate the compliance of the actuator. One actuator controlled the location of the resting position and the other actuator changed the tension of the spring, which resulted in changes in stiffness. The actuator was designed for more energy efficient walking and running in legged locomotion. In [9], the output stiffness of the joint was changed by adjusting transmission ratio using a lever arm of variable effective length. In [10], a mechanical impedance adjuster was designed for a robot manipulator. In order to change stiffness of the joint, the effective length of the leaf spring was changed using a lead-screw mechanism.

In antagonistic configuration, nonlinear springs were necessary to change stiffness of the joint. In order to realize nonlinear springs, rolamite springs were used in [11] since nonlinearity of the spring depends on the shape of the spring. Tonietti *et al.* used a timing belt and linear springs to realize nonlinear springs in [12]. Since the power of the motors were transmitted through the timing belt, the strength of the belt limited the maximum allowable payload. The existence of the idle pulley made the joint bulky. To overcome such disadvantages, another design was presented in [13]. The presented VSA-II used a four-bar linkage system to transmit the power, which showed more robustness and larger load bearing capability. Using 4-bar linkages and leaf springs, the stiffness of the joint was varied via changing the effective length of the springs in [14]. It had limitations in reducing its volume and weight since the leaf spring was attached to the axis in radial direction.

In [15], a powered elbow exoskeleton for rehabilitation was equipped with a variable impedance antagonistic actuation system. For variable stiffness, nonlinear springs were connected to the joint through cable transmission. In [16], an active variable stiffness exoskeleton robot system was introduced. In order to change the stiffness of the system, the effective length of the leaf spring was changed using a motor.

This research was supported by KIST Institutional Program(2E24721).

Jaewook Oh, Soojun Lee, and Junho Choi are with the Center for Bionics, Korea Institute of Science and Technology, Seoul, Korea {jaewookoh, sjlee, junhochoi}@kist.re.kr
Myotaeg Lim is with the school of electrical engineering, Korea university, Seoul, Korea mlim@korea.ac.kr

In this paper, a mechanically adjustable stiffness actuator is presented. It is designed for an exoskeleton for rehabilitation of stoke patients. Stiffness of the actuator is varied by changing the effective length of cantilever springs which is attached to the axis in the axial direction through a torque limiter. A double-tripod parallel mechanism is used to change stiffness of the spring. Due to the torque limiter which is released when an external torque greater than preset threshold value, excessive torque is not transmitted from and to the link. A concept of the rehabilitation robot for knee joint using the MASA is introduced. By changing the stiffness of the MASA, the amount of assistance by the robot was adjusted.

In Section II, the design of the MASA is explained. Using the double-tripod parallel mechanism, the MASA changes the effective length of the cantilever springs, which results in stiffness change. Stiffness of the MASA is derived in Section III. In Section IV, controlling stiffness and position of the MASA is explained. A robot for knee rehabilitation using the MASA is introduced in Section V. Experimental result is presented in VI and conclusion follows in VII.

II. Design of MASA

This section explains the design of the MASA. The MASA consists of a double-tripod parallel mechanism, three identical cantilever springs, and a torque limiter. The double-tripod parallel mechanism is composed of two "input bases" and one "output plate," which is located between the input bases. While the input bases rotate about an axis without translational movement along the axis, the output base makes rotational and translational movements with respect to the axis. Each input base is connected to the output plate with three rigid links via universal and ball joints, see Fig. 1. The lengths of the rigid links are greater than a half of the distance between the input bases. Therefore, relative angular positions of the input bases determines the translational location of the output plate. The input bases are actuated by two identical actuators.

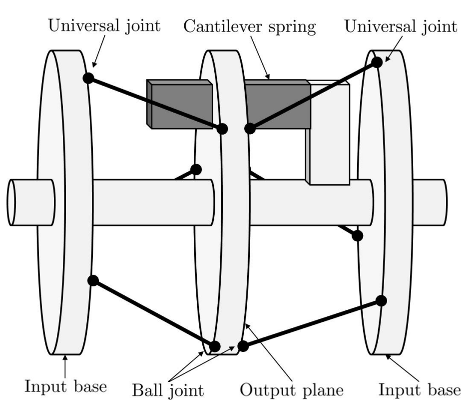

Fig. 1. Schematics of the double-tripod parallel mechanism and a cantilever spring. For simplicity, only one spring is shown.

The output plate has openings with two rollers. The cantilever springs are inserted through the openings and held by the rollers. "Spring holder," to which the other end of each spring is attached, rotates freely about the axis. However, it does not move along the axis. Note that since the distance between the input bases remains constant, the location of the output plate along the axis is determined by the relative angular displacement of the input bases. Therefore, the effective length of the cantilever springs, which is the distance between the output plate and the spring holder, is changed as the angular displacement of the actuators changes. The torque limiter consists of balls and a

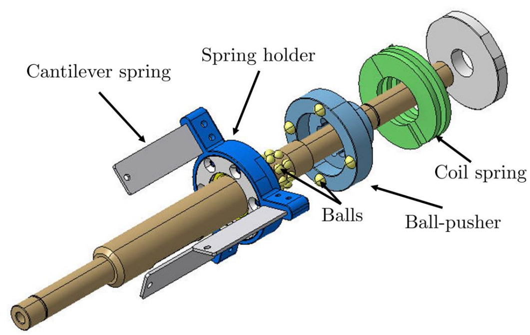

Fig. 2. Design of the torque limiter. There are detents for the balls on the surface of the spring holder. When excessive torque is applied, the torque pushes the balls out of the detents to make the torque limiter released.

linear coil spring. The balls are held by "ball-pusher." The ball-pusher is free to move along the axis but it does not make any relative rotational movement with the axis. The ball-pusher is pushed against the spring holder by the precompressed coil spring. There are detents for the balls on the contacting surfaces of the spring holder, see Fig. 2.

When an external torque is less than the threshold, the spring holder and the ball-pusher are engaged, connecting the cantilever spring and the axis together. If the external torque at the axis is greater than the threshold, the balls in the detents are pushed out of the detents and the ball-pusher becomes free to rotate. Then, the axis rotates independent of the spring holder, preventing an excessive torque from and to the axis is transmitted. The threshold is determined by the spring force of the coil spring.

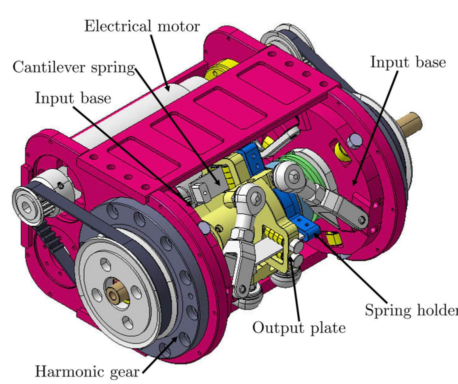

Fig. 3. Designed MASA. It is actuated by two identical electrical motor and harmonic gears.

Designed MASA is shown in Fig. 3. The input bases are actuated by electrical motors with harmonic gears. Since the load at the axis is shared by the actuators, the required torque from the actuators is reduced, which results in reduction of the actuators in size and weight.

III. Stiffness of the joint

Stiffness of the MASA is determined by the effective length of the three identical cantilever springs. The effective length of the spring is defined as the distance between the spring holder and the output plate, which is controlled by two identical actuators.

Let l_e be the effective length of the spring and let w_s be the width of the spring. Let r_s be the distance from the center of the axis. Let t_s be the thickness of the spring, see Fig. 4. Then, since there are three identical springs held by

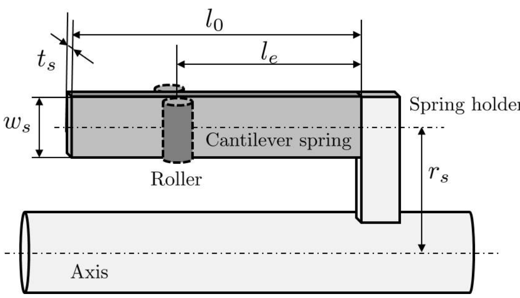

Fig. 4. Schematics of the cantilever spring and axis

the spring holder, the force at the end of each spring due to the external torque is as follows.

$$F = \frac{\tau}{3r_s}, \tag{1}$$

where τ is the external torque. The force makes the springs bent and the deflection of the spring is given as follows.

$$d\delta = \frac{4l_e^3}{Ew_s t_s^3}F, \tag{2}$$

where E is the Young's modulus of the cantilever spring. The angular displacement of the axis due to the deflection is given as

$$d\theta = \frac{d\delta}{r_s}. \tag{3}$$

Combining (1), (2), and (3) together results in the torsional stiffness as follows.

$$\sigma = 3\frac{Ew_s t_s^3}{4l_e^3}r_s^2. \tag{4}$$

The torsional stiffness is changed if the effective length of the spring varies. As the effective length of the spring becomes smaller, the torsional stiffness becomes larger. Note that since the maximum stiffness is not bounded, the range of stiffness is determined by the minimum stiffness of the MASA. Since the stiffness is determined by the shape of the springs, it is possible to change the range of stiffness by designing the cantilever springs (i.e. width, thickness of the springs, etc.)

IV. Changing position and stiffness

Since the resting position of the cantilever spring is the angular position of the output plate and the stiffness of the MASA depends of the location of the output plate along the axis, it is necessary to calculate the position of the output plate.

Let q_1 and q_2 be the angular positions of the actuators. Let l be the length of the rigid link connecting the input bases and the output plate. The radii of the input bases and the output plate are designed to be identical, which are denoted by r, see Fig. 5. Let q_0 be the desired angular position of

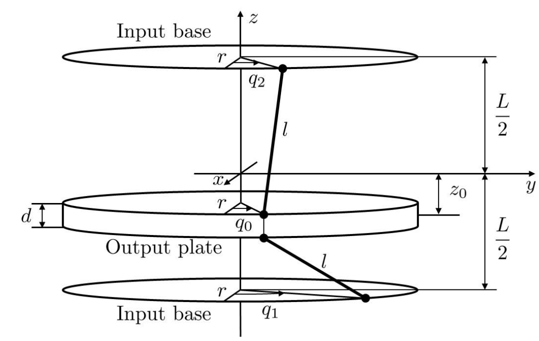

Fig. 5. Schematics of the double-tripod parallel mechanism.

the output plate and let z_0 be the translational position of the output plate. For desired z_0 and q_0, required positions of the actuators are given as follows.

$$q_1 = 2\sin^{-1}\left(\frac{1}{2r}\sqrt{l^2 - \left(z_0 - \frac{d}{2} + \frac{L}{2}\right)^2}\right) + q_0, \tag{5}$$

$$q_2 = 2\sin^{-1}\left(\frac{1}{2r}\sqrt{l^2 - \left(\frac{L}{2} - z_0 - \frac{d}{2}\right)^2}\right) + q_0. \tag{6}$$

Let a coordinate transform be defined as follows.

$$\begin{bmatrix} \zeta_1 \\ \zeta_2 \end{bmatrix} = \begin{bmatrix} \frac{q_1 - q_2}{2} \\ \frac{q_1 + q_2}{2} \end{bmatrix}. \tag{7}$$

Then,

$$\begin{aligned} \zeta_1 &= \sin^{-1}\left(\frac{1}{2r}\sqrt{l^2 - \left(z_0 - \frac{d}{2} + \frac{L}{2}\right)^2}\right) \\ &- \sin^{-1}\left(\frac{1}{2r}\sqrt{l^2 - \left(\frac{L}{2} - z_0 - \frac{d}{2}\right)^2}\right), \end{aligned} \tag{8}$$

$$\begin{aligned} \zeta_2 &= \sin^{-1}\left(\frac{1}{2r}\sqrt{l^2 - \left(z_0 - \frac{d}{2} + \frac{L}{2}\right)^2}\right) \\ &+ \sin^{-1}\left(\frac{1}{2r}\sqrt{l^2 - \left(\frac{L}{2} - z_0 - \frac{d}{2}\right)^2}\right) + q_0. \end{aligned} \tag{9}$$

Note that (8) is a function of z_0 only and invertible. Equation (9) is a functional of z_0 and q_o and invertible if z_0 is given.

V. Knee Rehabilitation Robot with MASA

The concept of rehabilitation robot with MASA is shown in Fig. 6. A shank of a patient is fixed with a link, which is actuated by the MASA. The resting position of the MASA is controlled to track a desired trajectory with different stiffness. Due to the springs, the patient is allowed to move away from the desired trajectory. The patient is asked to follow the joint trajectory while the performance of the patient, which is the actual position of the link, is shown on the display. If the patient moves away from the desired trajectory, torque by the spring helps the patient to follow the trajectory. The amount of assistance is determined by the stiffness of the MASA. According to the performance of the patient, the stiffness of the MASA is adjusted by the therapist.

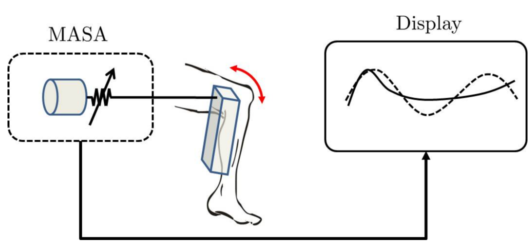

Fig. 6. Concept of rehabilitation robot. Shank of a patient is attached to MASA through a link.

Note that because of the springs and the torque limiter, physical safety of the patient is ensured in case of unexpected involuntary muscle activities such as spasticity during the session.

VI. Experiment

The implemented MASA is shown in Fig. 7. Two input bases are actuated by two identical electrical motors through harmonic gears and timing belts. The gear ratio of the harmonic gear is 100:1 and the pulley for the timing belt is 3:1, which makes the overall gear ratio to be 300:1. Power of each electrical motor is 200W. Estimated maximum torque at the output shaft of the MASA is 64.77Nm. Since the average torque produced by a knee during walking is 34.74 Nm [17], The MASA generates sufficient torque for knee rehabilitation exercise. Detailed model parameters are listed in Table I.

Parameter	Value
Mass of the MASA	$1.7kg$
Dimension of the MASA	$156 \times 112 \times 83mm$
Size of cantilever spring	$10 \times 30 \times 1mm$
Young's modulus of cantilever spring	210 GPa
Max. stiffness of the MASA	$173Nm/rad$
Min. stiffness of the MASA	$71Nm/rad$
Length of rigid link	$38mm$
Distance between input bases	$69mm$
Radius of input bases and output plate	$28mm$

TABLE I

Model parameters of the implemented MASA

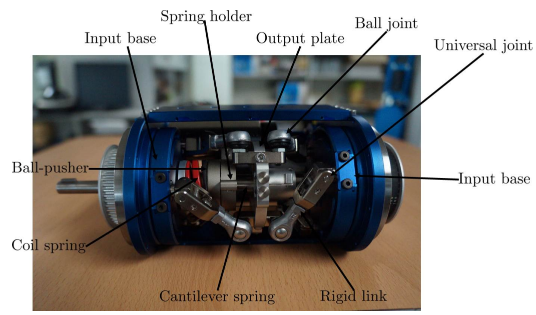

Fig. 7. Implemented MASA. Two input bases are actuated by electrical motors with harmonic gears. Each input base is connected to the output plate using three rigid links.

Fig. 8 shows the experimental setup to evaluate the MASA. The MASA is attached to a link through a torque sensor, which measures the external torque applied at the axis. The positions of the axis and the actuators are measured by the encoders.

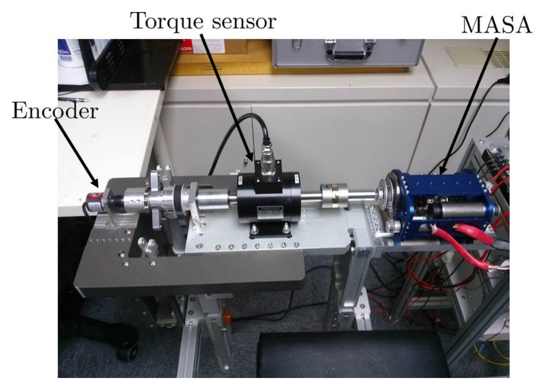

Fig. 8. Experimental setup. A link that is not shown in the figure is attached to the axis through a torque sensor in order to measure the torque at the axis. An encoder is connected to the axis for position measurement.

Estimation of torque by the springs is shown in Fig. 9. The position of the axis is measured using the position encoder while external torques are applied to the axis of the MASA with different angular displacement of the actuators. For estimation, the measured link position and torque data are fitted with linear functions. As the angular displacement of the MASA becomes larger, the effective length of the cantilever springs becomes longer, which results in lower stiffness of the MASA. Maximum stiffness of the MASA is $173Nm/rad$ and minimum stiffness is $71Nm/rad$. Maximum angular displacement of the actuators is $0.72rad$, which is limited by the dimensions of the cantilever springs and the rigid links connecting the input bases and the output plate.

Frequency response of the MASA is shown in Fig. 10 and Fig. 11. Frequency response of the position of the MASA is in Fig. 10.The 3dB cutoff frequency is 2.4Hz. Fig. 11 shows the frequency response of stiffness of the MASA. The 3dB cutoff frequency is about 4.5Hz.

The experimental result to measure the threshold torque of the torque limiter is shown in Fig. 12. An external torque

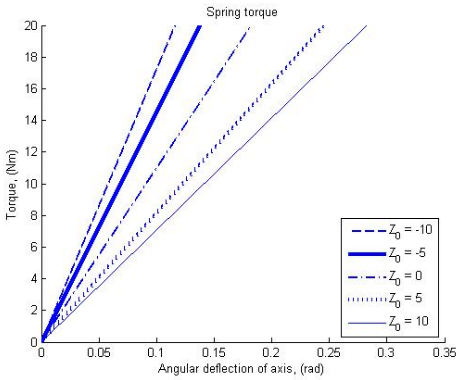

Fig. 9. Estimation of torque by the cantilever spring due to external torque. As the angular displacement of the actuator becomes larger, the stiffness of the MASA decreases.

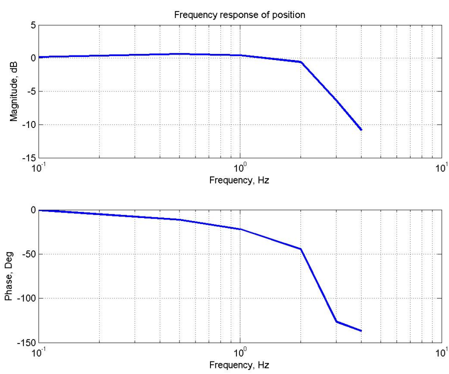

Fig. 10. Position bandwidth of the MASA. The 3dB cutoff frequency is about 2.4Hz

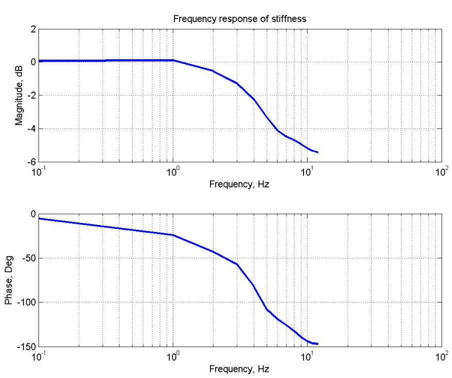

Fig. 11. Frequency response of stiffness. The 3dB cutoff frequency is about 4.5Hz

is applied at the link until the torque limiter is released while the external torque is measured by the torque sensor. The measured threshold is about 10Nm. When the torque limiter is released, the external torque is not transmitted from and to the axis, which makes the measured external torque converges to zero. The link becomes free to rotate if the torque limiter is released.

Fig. 13 is the prototype of the knee rehabilitation robot with MASA. A link with a brace, where the shank of the patient is fixed, is actuated by the MASA.

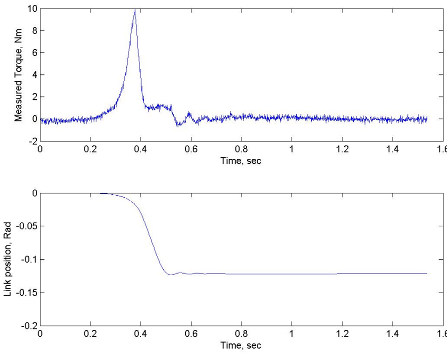

Fig. 12. Measured threshold of the torque limiter. The threshold is about 10Nm.

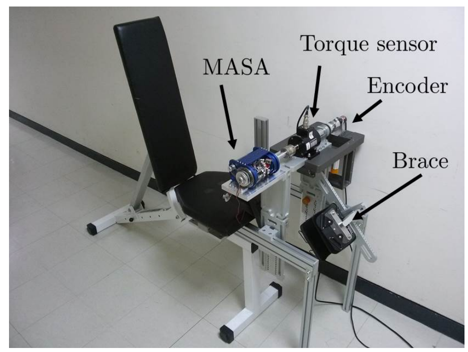

Fig. 13. Implemented rehabilitation robot using MASA

For experiment, a mass is attached to the link, which is moved by the MASA to follow a sinusoidal trajectory. Based on the estimation of human shank in [18], the mass and the position of the mass are determined to be 2.5kg and 0.2m from the knee joint, respectively. The frequency of the trajectory is 0.3Hz and the magnitude is about 23 degrees. Due to the range of motion of the knee, the trajectory is offset by 50 degrees. The positions of the link is measured with 5 different stiffness. Fig. 14 shows the trajectory of the link with different stiffness of the MASA. As the stiffness becomes smaller, the error becomes larger, which indicates lower stiffness of the MASA allows more freedom for the patient to move away from the desired trajectory. Therefore, the stiffness of the MASA changes the amount of assistance by the robot.

Fig. 15 shows the position of the link when human muscle is activated. A male subject wore the robot and was asked not to generate any torque at the knee. After a while, the subject was asked to activate the muscle to follow a sinusoidal trajectory with frequency of 0.2Hz and magnitude of 0.4rad. When the muscle was activated, the trajectory error was reduced without changes in stiffness of the MASA due to the torque generated by the subject. The torque necessary to reduce the error was generated by the subject and was proportional to the error, which was directly related to the stiffness. Therefore, it was possible to vary the amount of

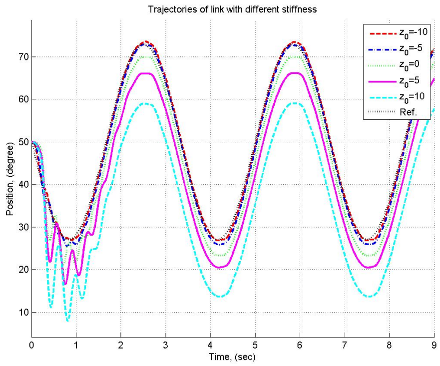

Fig. 14. Trajectories of the link with different stiffness

assistance by the robot via changing the stiffness.

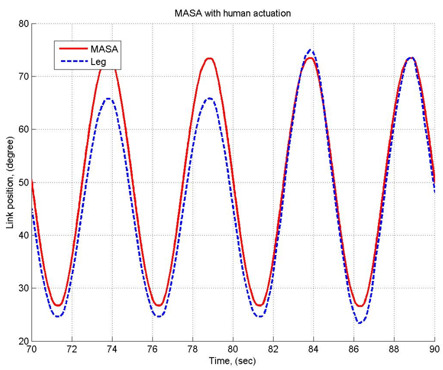

Fig. 15. Changes in the trajectory of the link when the muscle of the subject is activated. The frequency of the trajectory is 0.2Hz and the magnitude is 0.4rad. The position error is reduced with activation of the muscle.

VII. CONCLUSIONS

This paper presented the Mechanically Adjustable Stiffness Actuator(MASA) with a torque limiter for a knee rehabilitation robot. The MASA consisted of a double-tripod parallel mechanism, cantilever springs, and a torque limiter. Input bases of the double-tripod parallel mechanism, which were connected to output plate with rigid links, were actuated by two identical electrical motors with harmonic gears. Since the output plate hold one end of each cantilever spring, the position of the output plate determines the angular position of the resting position and stiffness of the MASA. The other end of each cantilever spring was connected to the axis through a torque limiter, which was released when an excessive external torque was applied at the axis.

Experimental results showed that stiffness of the MASA was changed as the angular displacement of the actuators was changed. The torque limiter was released by an excessive torque applied to the axis and prevented the torque being transmitted from and to the axis.

The robot using MASA for knee rehabilitation was introduced. Since the amount of assistance by the robot decreased as the stiffness of the MASA, the level of assistance was possible to be adjusted with the stiffness according to the patient.

REFERENCES

[1] G. A. Pratt and M. M. Williamson, “Series elastic actuator,” in *Proceedings of the IEEE/RSJ Conference on Intelligent Systems and Robots*, Pittsburgh, PA, USA, Aug 1995, pp. 399–406.

[2] C. J. Walsh, D. Paluska, K. Pasch, W. Grand, A. Valiente, and H. Hurr, “Development of a lightweight, under actuated exoskeleton for load-carrying augmentation,” in *Proceedings of the IEEE International Conference on Robotics and Automation*, Orlando, Florida, May 2006, pp. 3485–3491.

[3] H. K. Kwa, J. H. Noordern, M. Missel, T. Craig, J. E. Pratt, and P. D. Neuhaus, “Development of the IHMC mobility assist exoskeleton,” in *Proceedings of the IEEE International Conference on Robotics and Automation*, Kobe, Japan, May 2009, pp. 2556–2562.

[4] J. F. Veneman, R. Ekkelenkamp, R. Kruidhof, F. C. T. van der Helm, and H. van der Kooij, “A series elastic- and bowden-cable-based actuation system for use as a torque actuator in exoskeleton-type robots,” *International Journal of Robotics Research*, vol. 25, no. 3, pp. 261–281, March 2006.

[5] J. F. Veneman, R. Kruidhof, E. E. G. Hekman, R. Ekkelenkamp, E. H. F. Van Asseldonk, and H. van der Kooij, “Design and evaluation of the LOPES exoskeleton robot for interactive gait rehabilitation,” *IEEE transactions on Neural Systems and Rehabilitation Engineering*, vol. 15, no. 3, pp. 379–386, September 2007.

[6] H. Vallery, J. Veneman, E. van Asseldonk, R. Ekkelenkamp, M. Buss, and H. van der Kooij, “Compliant actuation of rehabilitation robots,” *IEEE Robotics & Automation Magazine*, pp. 60–69, September 2008.

[7] S. Wolf, O. Eiberger, and G. Hirzinger, “The DLR FSJ: Energy based design of a variable stiffness joint,” in *Proceedings of the IEEE International Conference on Robotics and Automation*, Shanghai, China, May 9–13 2011, pp. 5082–5089.

[8] J. W. Hurst, J. E. Chestnut, and A. A. Rizzi, “The actuator with mechanically adjustable series compliance,” *IEEE Transactions on Robotics*, vol. 26, no. 4, pp. 597–606, August 2010.

[9] S. S. Groothuis, G. Rusticelli, A. Zucchelli, S. Stramigioli, and R. Carloni, “The vsaUT-II:a novel rotational variable stiffness actuator,” in *Proceedings of the IEEE International Conference on Robotics and Automation*, Saint Paul, Minnesota, USA, May 14–18 2012, pp. 3355–3360.

[10] T. Morita and S. Sugano, “Design and development of a new robot joint using a mechanical impedance adjuster,” in *Proceedings of the IEEE International Conference on Robotics and Automation*, Nagoya, Japan, May 1995, pp. 2469–2475.

[11] C. English and D. Russell, “Implementation of variable joint stiffness through antagonistic actuation using rolamite springs,” *Mechanism and machine theory*, vol. 34, pp. 27–40, 1999.

[12] G. Tonietti, R. Schiavi, and A. Bicchi, “Design and control of a variable stiffness actuator for safe and fast physical human/robot interaction,” in *Proceedings of the IEEE International Conference on Robotics and Automation*, Barcelona, Spain, April 2005, pp. 526–531.

[13] R. Schiavi, G. Grioli, S. Sen, and A. Bicchi, “VSA-II: a novel prototype of variable stiffness actuator for safe and performing robots interacting with humans,” in *Proceedings of the IEEE International Conference on Robotics and Automation*, Pasadena, CA, USA, May 2008, pp. 2171–2176.

[14] J. Choi, S. Hong, W. Lee, S. Kang, and M. Kim, “A robot joint with variable stiffness using leaf springs,” *IEEE Transactions on Robotics*, vol. 27, no. 2, pp. 229–238, 2011.

[15] N. Vitiello, T. Lenzi, S. Roccella, S. M. M. De Rossi, E. Cattin, F. Giovacchini, F. Vecchi, and M. C. Carroza, “NEUROExos: A powered elbow exoskeleton for physical rehabilitation,” *IEEE Transactions on Robotics*, vol. 29, no. 1, pp. 220–235, February 2013.

[16] R.-J. Wang and H.-P. Huang, “AVSER-active variable stiffness exoskeleton robot system: Design and application for safe active-passive elbow rehabilitation,” in *IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, Kaohsiung, Taiwan, July 2012, pp. 220–225.

[17] J. J. Eng and D. A. Winter, “Kinetic analysis of the lower limbs during walking: what information can be gained from a three-dimensional model?” *Journal of Biomechanics*, vol. 28, no. 6, pp. 753–758, 1995.

[18] P. de Leva, “Adjustments to Zatsiorsky-Seluyanov’s segment inertia parameters,” *Journal of Biomechanics*, vol. 29, no. 9, pp. 1223–1230, 1996.