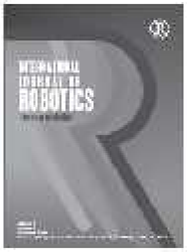


INTERNATIONAL JOURNAL OF ROBOTICS
(THEORY AND APPLICATIONS)
E-mail: IJR@kntu.ac.ir

Conceptual Design of a Gait Rehabilitation Robot

Ali Mirzaie Saba[a], Majid M. Moghaddam[b, *], Abbas Ehsaniseresht[c] and Mohammad D. Hasankola[d]
[a] Faculty of Mechanical Engineering, Tarbiat Modares University, Tehran, Iran.
[b] Faculty of Mechanical Engineering, Tarbiat Modares University, Tehran, Iran, E-mail address: m.moghadam@modares.ac.ir.
[c] Department of mechanical Engineering, Hakim Sabzevari University, Sabzevar, Iran.
[d] Faculty of Mechanical Engineering, Tarbiat Modares University, Tehran, Iran

ARTICLE INFO

Article history:
Received: December 29, 2014.
Received in revised form:
April 9, 2015.
Accepted: May 11, 2015.

Keywords:
Rehabilitation
Treadmill Training
Exoskeleton
Backdrivability

ABSTRACT

Gait rehabilitation using body weight support on a treadmill is a recommended rehabilitation technique for neurological injuries, such as spinal cord injury. In this paper, a new robotic orthosis is presented for treadmill training. In the presented design the criteria such as low inertia of robot components, backdrivability, high safety and degrees of freedom based on human walking are considered. This robot is composed of a leg exoskeleton for leg control and a segment for pelvis control. In the exoskeleton two degrees of freedom are considered for the hip joint and one for the knee joint. Also two degrees of freedom are considered for the pelvis joints. The inertia of moving components and the required force for the robot motion are measured to evaluate the robot backdrivability and transparency. Further, a walking algorithm is implemented on the robot and is tested on a human subject. Evaluation of the design showed that the robot is suitable for gait rehabilitation exercises.

1. Introduction

Utilizing robots in gait rehabilitation applications is considered in the last decades for the automation of patients' rehabilitation exercises. These robots can substitute the physiotherapist training, and are particularly suitable when the physiotherapy exercises are very intensive. So, the robot can reduce the therapist intensity and also can increase exercise time [1].

Various robotic Orthosis are presented for gait rehabilitation in the recent years such as Lokomat [2], LOPES [3], ALEX [4] and the robot with pneumatic actuators POGO [5], that only Lokomat is commercialized. Each of the previously presented robots has particular problems which makes them have low performance. For example, Lokomat has limited degrees of freedom which prevent it from possibility of natural walking. Also its mechanism has high inertia which reduces robot transparency [6]. In the robot LOPES, using cable has caused some problems such as cable friction and cable sliding at high torques [3, 7-8]. Pneumatic actuators are used in robot POGO. Due to nonlinear behavior of these actuators, their force control causes different problems.

The present paper introduces a new robot for gait rehabilitation. The degrees of freedom in this robot are considered based on human walking in order to provide the possibility of natural walking for patient. The robot is designed to minimize the friction effects of transmission and inertia set of robot components. The design criteria, the criteria realization and the results of design are presented in this paper.

2. Robot design

2.1. Design criteria

Literature review of the gait rehabilitation robots gives the following design criteria [1, 3, 5, and 9]:

1. The patient should be able to have active participation in exercises. Non-active training will decrease the effects of rehabilitation exercises.
2. The possibility of natural motion of healthy human being should be provided during rehabilitation exercises.

In order to provide patient participation, the robot should be designed such that the force control methods such as impedance control are implemented. To achieve this, the effects of friction and inertia should be minimized in robot design [3, 7, and 10]. The significant point is that backdrivable actuators should be used and also the robot components should be possibly light and frictionless. On the other hand, the robot should have enough degrees of

---

[*] Corresponding author, Tel: +989123278920

freedom in order to patient have possibly natural motion. Another criterion which should be considered in all the design steps is that the robot should have high safety to keep the patient out of harms.

2.2. Proposed design

The robot design basis is body weight supported treadmill training (BWSTT). To achieve this, a part of body weight is balanced using a supporting system. Then the patient is placed on the treadmill, and the walking algorithm is applied to the leg using an exoskeleton to perform rehabilitation exercises. The robot model and connection braces between robot and body are shown in Fig.2.

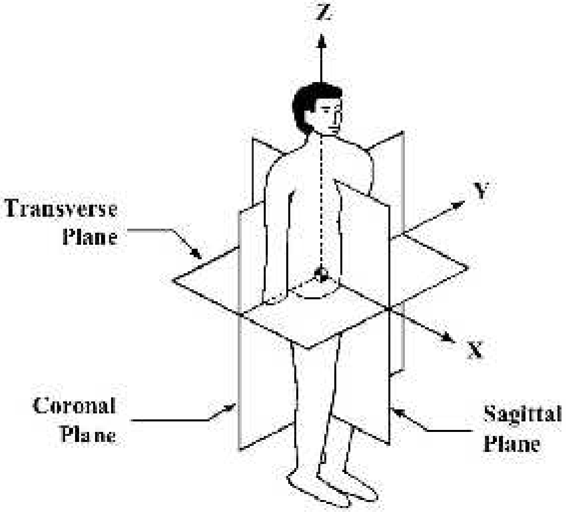


Fig.1: Reference planes of the human body [12].

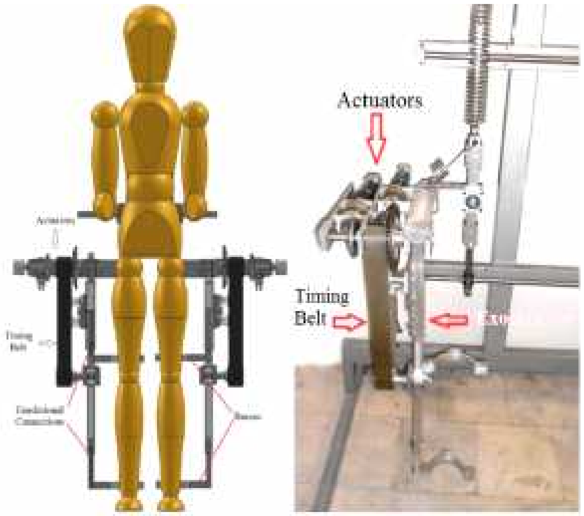
The reference planes are shown in Fig.1. In the robot design, two active degrees of freedom are considered for hip and knee joints (one for hip and one for knee) which are in sagittal plane. Also hip joint has a passive degree of freedom in the coronal plane which is supported by a spring. The pelvis segment also has the possibility of displacement to upward and downward and to left and right in coronal plane which are passively balanced by springs (Fig.3).

To attain pelvis degrees of freedom, minimum weight and friction is considered. To achieve this, some linear guides are used. These degrees of freedom are designed such that the robot is provided with the necessary range of motion (table 2). The pelvis degrees of freedom are shown in Fig.3.

To reduce the inertia of moving parts, Alloy Aluminum is used for components' design. Also the knee joint actuator is shifted above using a timing belt in order to minimize the inertia of components.

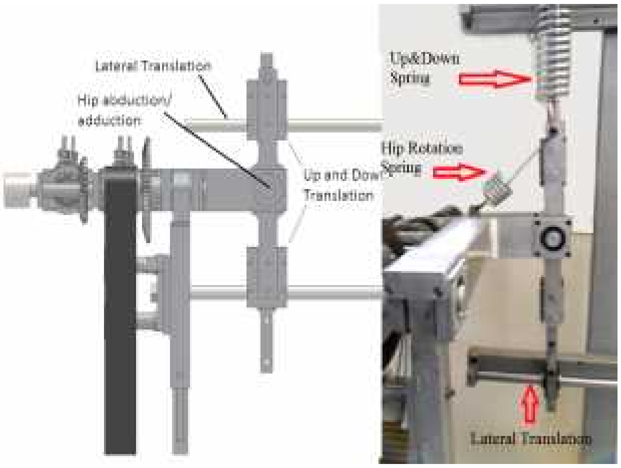
In order to the robot can be adjustable for different people, the links are designed cascade to have variable length (Fig.2). To do this, the belt length can adjust proportional to the link length with an additional mechanism (Fig.4).

The active degrees of freedom in the robot are controlled by using the electrical motors.



(a) (b)

Fig.2: (a) Software model, (b) Prototype with artificial leg.



(a) (b)

Fi.g3: (a) Pelvis degrees of freedom and hip abduction/adduction. (b) Prototype with compensator springs

Table 1. Active Degrees of freedom specification

Degrees of freedom	**Range of motion**	**Maximum torque of actuator**	**Maximum velocity of actuator**
Hip joint (active)	-30/ +60(deg)	50 N.m	2 rad/s
Knee joint (active)	0/ + 90(deg)	30 N.m	5.5 rad/s

Table 2. Passive Degrees of freedom specification.

Degrees of freedom	**Range of motion**
Hip joint lateral motion	-10/+10(deg)
Pelvis lateral motion	-10/+10 cm
Pelvis up/down motion	-10/+10 cm

The motors are Maxon/EC45/brushless/250watt whit gear ratio 100 for knee joint and 170 for hip joint because we need low velocity and high torque in hip joint and vice versa. The motor and gearbox set are chosen such that provide necessary torques and angular velocities for joints. The suitable ranges for velocity and displacement are derived from [3] and [12]. Table 1 and 2 give each joint specification. The necessary tests are performed to confirm the mentioned specification for active DOFs are performed. To achieve this, while the other DOFs are locked, torque is applied separately to proposed joint and the obtained torque is measured.

2.3. Timing belt adjustment mechanism

The motor of the knee joint is positioned on the robot upper chassis and the motion is transferred from the pulley and timing belt to the knee joint. On the other hand, the arm length should be changed for various users. To achieve this, a mechanism such as that shown in Fig. 4 is considered. Using this mechanism, the belt length can be changed around 12 cm and the belt can be fixed again. For this purpose, two spindle pulleys are used. Based on the assembly shown in Fig. 4, the adjustment of the belt is provided by the spindle pulley rotation.

Fig. 4: Belt adjustment mechanism

2.4. Spring designs

The springs are designed to compensate the weight of the robot components. Besides, it is attempted to select the constant of springs such that negligible forces are exerted on the user during movement. For this purpose, the forces of springs are calculated based on the weight of robot's assembly. Then a reasonable initial displacement is considered for the springs so that the springs compensate the weight.

In choosing the initial displacement, it should be noted that if high initial displacement is considered, the spring constant will be low. Thus the static force exerted on patient during movement will be lower. On the other hand, in order to reduce the effect of dynamic forces, the length of spring is selected such that the natural frequency of the spring is equal to the maximum working frequency of the robot. The result is that, besides the compensation of static forces, the spring can fully compensate the dynamic forces in high frequencies and therefore very little force is exerted on patient during movement. This frequency is obtained to be 1 Hz for the up and down movement.

For the design of hip joint abduction/adduction spring, only the weight force has been taken into account because the dynamic forces have been negligible.

The constants of springs are shown in Table 3. In case of Hip joint spring, it should be noted that the spring force is converted to a torque around the rotation axis. Thus the equivalent spring rotational constant will be equal to 1.625 N.m/deg. In the robot initial design, no spring is considered for the lateral movement because the patient lateral movement is compensated by the body weight support.

Table 3. Specifications of passive degrees of freedom and springs

Dof	Range of motion	Spring Constant (N/m)
Rotation of hip joint about X axis	-10/+10 (deg)	7500
Lateral pelvic displacement	-10/+10 (cm)	-
Up and down displacement	-10/+10 (cm)	600

2.5. Safety

As the robot has direct human interaction, the safety is of crucial importance. Two solutions are considered for the robot safety provision. The first solution is using mechanical locks at the end of moving parts of each degree of freedom. These locks are able to sustain the applied forces. The second solution is using emergency switch which turns of the robot.

2.6. Force control

To achieve backdrivability of the actuator and applying force control, series elastic actuators are used. For this purpose, an elastic element is put between the motor and robot arm. The model of these actuators, which are used in the robot, is shown in Fig. 5.

Using the force feedback in this actuator, the backdrivability of the motor assembly and transmission is considerably increased. Besides this, the force feedback in this actuator can be used for the force control such that, using the law of Hook, the spring displacement can be converted to the force. The details for the design of this actuator and its results can be found in [11].

Use of these actuators has various advantages, some of which are backdrivability, high force fidelity and impact resistance. The reason is that the actuator inertia and friction are not transferred to the user and the other hand the user movements and impacts are not directly transferred to the motor.

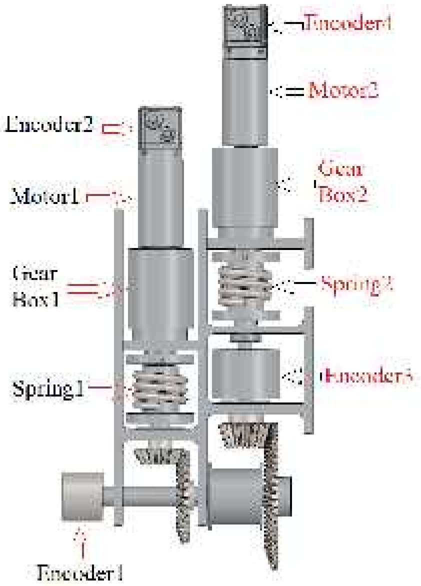


Fig. 5: Realization of series elastic actuators

3. Simulation of the robot forces

The general equations for the robot motion are as follows:

$$\tau = M(\theta)\ddot{\theta} + V(\theta,\dot{\theta}) + G(\theta) \quad (1)$$

The robot operation is such that the upper body is fixed and the feet move on the treadmill. Therefore, a tow DOFs robot model is used for the robot simulation. The main difference of this model with the reality is that, in the real motion, the upper body moves a little up and down but here the upper body is considered to be fixed. However, noting the simulations performed, this assumption has a negligible error for the calculation of dynamic forces, and these effects are neglected. So we have:

$$\begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \end{bmatrix} + \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} + \begin{bmatrix} G_1 \\ G_2 \end{bmatrix} \quad (2)$$

The equations of motion are solved by MATLAB coding. The inputs of this code include angles, angular velocities and angular accelerations of healthy human. The output of the code is the torque required for each joints. The results of the equations being solved for torques of the joints are shown in Fig.6.

In these diagrams, only the forces required for the robot motion are calculated. In order to calculate the force required for the design of robot, the force exerted by the patient should be added. However, since a part of the force in rehabilitation exercises is compensated by the body weight support, about 60 present of the patient forces are taken into account in design process (Fig.7 and Fig.8). The values of these forces are derived from [13].

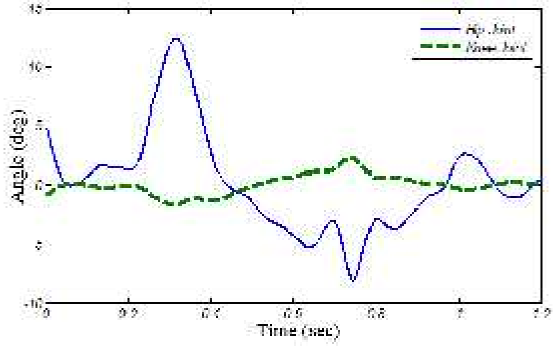


Fig. 6. Dynamic forces of robot structure

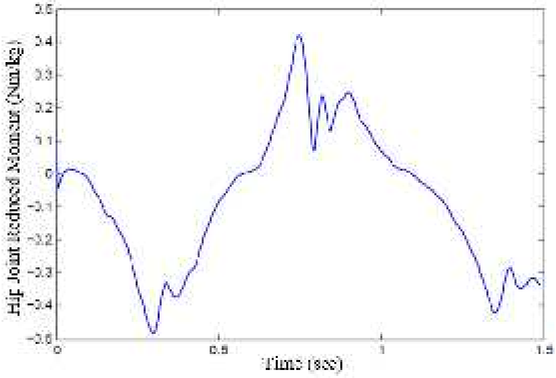


Fig.7: Moment of hip joint (When 60% of weight is exerted) N.m/kg [13]

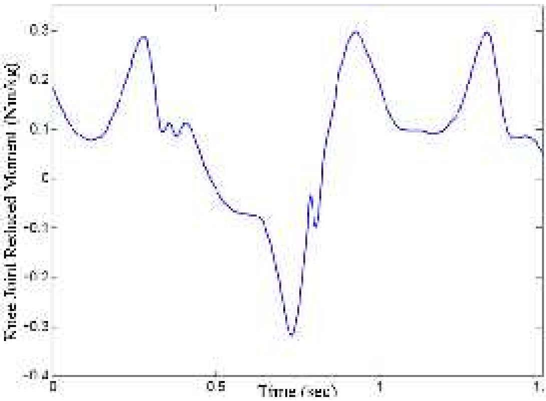


Fig. 8. Moment of knee joint (When 60% of weight is exerted) N.m/kg [13]

4. Robot performance

4.1. Measurements

As it is mentioned, the robot is designed to have minimum inertia of components. Table 4 shows the inertias of robot components.

Table 4. Inertia of robot components.

Robot Part	***L*** **(m)**	***Lc*** **(m)**	***m*** **(kg)**	***J1*** **(Kg.m2)**	***J2*** **(Kg.m2)**
Upper limb	0.43	0.23	2.9	0.063	0.23
Lower limb	0.37	0.14	1.0	0.015	0.05

In the table 4, J1 is the mass moment of inertia about mass center and J2 is the mass moment of inertia about proximal joint. *m* is link mass, *L* is the rod length and L_c is the Center of mass from proximal joint. It should be noted that as the length of components is variable, mean length is considered.

In order to know the resistance of robot against patient's free motion, the resistance force of joints is measured. In order to calculate both the static and dynamic forces, a particular test is designed. As the other degrees of freedom are locked, the hip and knee degrees of freedom are moved separately with 1 Hz frequency and the force required for this motion is measured. The amplitude of motion for knee and hip are 30 and 20 degrees respectively. The forces are measured using a force sensor which is installed at robot end. Motions are exerted by hand via the force sensor. As the motions are applied manually, the mentioned frequency is an approximation. Because the frequency of natural walking is about 1 Hz and less, these values are the maximum resistance forces in the robot working interval. Values of these forces are shown in table 5. These forces can show the value of robot inherent backdrivability.

Theoretical inertia torques also are shown in this table. The results are based on the mass moment of inertia in table 5. Difference between real and theoretical values is because of friction and gravity and is about 1N.m for hip and 2.5N.m for knee in imposed motion.

Table 5. Maximum resistance torques.

Degree of freedom	Force (N)	Distance (m) (from proximal joint)	Real resistance Torques (N.m)	Inertia torques (N.m)	Other (Friction&Gear Box) (N.m)
Knee joint	10	0.37	3.7	1.1	2.6
Whole leg	11	0.8	8.8	7.7	1.1

A similar test is performed in robot LOPES [3], but in this case the motors applied control forces in zero impedance mode. But the above values are calculated when the motors are off and did not apply any control forces. It should be mentioned that resistive torques can be reduced using a controller and friction compensation. This compensation is performed for the actuators and presented in [11]. We can reduce this resistive torques less than 1*N.m* by friction compensation [11].

4.2. Applying the walking algorithm

After performing initial tests on an artificial leg and insuring of the full safety of robot, human test is performed on a healthy human. Noting the discussions made in the introduction, the robot's main goal is providing the cooperative control for the patient so that the patient could have freedom during practice. To do this, an impedance control with a structure shown in Fig.9 is implemented. In this control, the path deviation of patient from the reference path can be varied by the variation of impedance gains. In higher gains, the impedance control acts as a position control and does not allow any deviations to the patient movement.

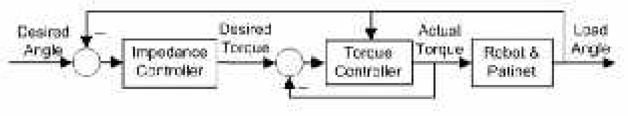


Fig.9: Schematic of the impedance controller [13]

In Fig. 10, the results of the test of robot in high gains on a healthy human are shown. Performance freedom can be provided to the patient by reducing the impedance gains. This is very important for patient improvement that the robot can provide freedom in motion so that patient can exert the force itself, not only moved by the robot.

The ability of changing gains is provided in robots software and the user's GUI, so that user can change these gains during the rehabilitation exercises [13].

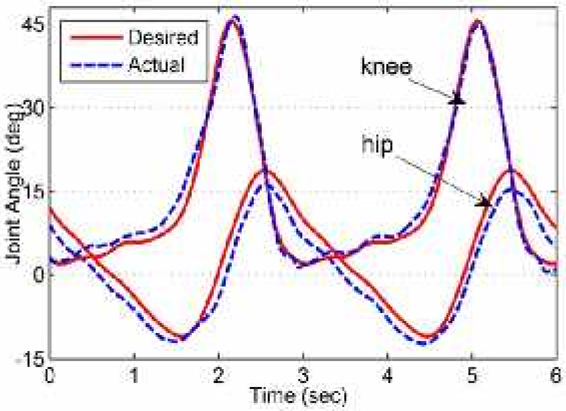


Fig10. The results of walking of a subject on the treadmill at the speed of 0.8 m/s in impedance control mode

Fig.11: Human test

5. Conclusion and future works

In this paper, a rehabilitation robot with a new design is presented which has low inertia and suitable degrees of freedom for moving legs. The inertia of robot components was presented in table 4. These values are lower than those for many other models such as robot LOPES [7]. Also it is attempted for the robot to be inherently backdrivable. This feature is shown in table 5.

Beside low inertia, in compare to some robots such as Lokomat, it has more degrees of freedom in hip joint and pelvis. The hip joint has rotation in coronal plane and pelvis has left and right translation in coronal plane addition to Lokomat degrees of freedom.By using timing belt, the robot is designed to minimize the friction effects of transmission and inertia set of robot components. In robot LOPES, there is similar solution by using cable transmission. But cable has some shortcomings such as slipping and friction. In this robot, timing belt solved these problems. Primary tests with artificial leg and healthy human show robot has enough capabilities to apply walking algorithm. In fact this test is the first step towards preparation of robot for patient tests. It can be concluded that the presented robot has the design criteria such as suitable degrees of freedom, low inertia and high safety and so is suitable for gait rehabilitation exercises. Of course it has good structure for implementing different methods of force control that will be carried out. During the tests, the subjects had considerable lateral translations when they left the treadmill handrails. One possible explanation is the lack of forward translation DOF for the robot. Because this DOF is fixed by the robot, undesired forces are exerted to the subjects during walking that makes difficult keeping their walking stable. When they hold the treadmill handrails, they use them for their stability. Although this problem is fixed by increasing the stiffness of spring in the lateral DOF of trunk, the forward translation will be considered in future improvements of robot.

One of the future works that will be attempted on the robot is to test it on the patients. As the next steps, different methods of force control such as path control will be applied on the robot.

6. References

[1] G. Colombo, M. Wirz and V. Dietz, Driven gait orthosis for improvement of locomotor training in paraplegic patient. Spinal Cord., Vol. 39, (2001), 252 – 255.

[2] S. Jezernik, G. Colombo, T. Keller, H. Frueh and M. Morari, Robotic Orthosis Lokomat: A Rehabilitation and Research Tool. International Neuromodulation Society, Vol. 6(2), (2003), 108-115

[3] 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. the 28th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, New York, Vol. 15(3), (2007), 379-386.

[4] S. K. Banala, S. K. Agrawal and J. P. Scholz, Active Leg Exoskeleton (ALEX) for Gait Rehabilitation of Motor-Impaired Patients. 2007 IEEE 10th International Conference on Rehabilitation Robotics, Noordwijk, The Netherlands, (2007), June 12-15, 401-407.

[5] D. J. Reinkensmeyer, D. Aoyagi, J. L. Emken, J. A. Galvez and W. Ichinose, Tools for understanding and optimizing robotic gait training. Journal of Rehabilitation Research & Development, August/September, Vol. 43(5), (2006), 657–670 .

[6] H. Vallery, M. Guidali, A. Duschau-Wicke and Robert Riener, Patient Cooperative Control: Providing Safe Support without Restricting Movement. IFMBE proceeding, (2009), 166-169.

[7] H. Vallery, J. Veneman, Compliant Actuation of Rehabilitation Robots, IEEE Robotics & Automation Magazine,Vol. 15(3), (2008), 60-69.

[8] 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 Torque Actuator in Exoskeleton-Type Robots. The International Journal of Robotics Research Vol. 25(3), (2006), 261-281.

[9] A. Duschau-Wicke, J. V. Zitzewitz, L. Lünenburger and R. Riener, Patient-Driven Cooperative Gait Training with the Rehabilitation Robot Lokomat. IFMBE Proceedings 22, (2008), 1616–1619.

[10] M. Wellner, M. Guidali, J. Von Zitzewitz and Robert Riener, Using a Robotic Gait Orthosis as Haptic Display-A Perception-Based Optimization Approach, the IEEE 10th International Conference on Rehabilitation Robotics, (2007), 81-88.

[11] M. D. Hasankola, A. Dashkhaneh, M. M. Moghaddam, A. Mirzaie Saba, Design of a rotary elastic actuator for use as torque-actuator in rehabilitation robots, First RSI/ISM International Conference on Robotics and Mechatronics, (2013), 505-510.

[12] Q. Wang, J. Qian, Y. Zhang, L. Shen, Zh. Zhang and Zh. Feng, Gait Trajectory Planning and Simulation for the Powered Gait Orthosis, the IEEE International Conference on Robotics and Biomimetics, Sanya, China, (2008), 1693-1697.

[13] A. Mirzaie Saba, Design, Simulation and Manufacturing of a Gait Rehabilitation Robot, MSc Thesis, Tarbiat Modares Univercity, (2012).

A. Mirzaie Saba received the M.S. degree in mechanical engineering from the Tarbiat Modares University, Tehran, Iran, in 2012.

In his M.Sc. thesis at the Robotics and mechatronics Laboratory of Tarbiat Modares University, he designed, simulated and manufactured new gait rehabilitation robot.

Majid M. Moghaddam is currently an Associate Professor, Applied Design Division, in the faculty of Mechanical Engineering at Tarbiat Modares University, Tehran, Iran. He received his Ph.D. degrees in mechanical engineering from University of Toronto, in 1997. His research interests include Rehabilitation Robotics, Haptic Robotics, Inspection Robotics, Robust H∞ Control and Flexible Robots.

Abbas Ehsaniseresht is currently an assistant professor in the department of Mechanical Engineering at Hakim Sabzevari University. He received his Ph.D. degrees in mechanical engineering from Tarbiat Modares University in 2014. His research interests are in the field of neurorehabilitation and rehabilitation engineering.

Mohammad D. Hasankola received the M.Sc. degree in mechanical engineering from the Tarbiat Modares University, Tehran, Iran, in 2012.

In the context of a M.S. thesis at the Robotics and mechatronics Laboratory of Tarbiat Modares University, he designed, simulated and manufactured and controlled a rotary series elastic actuator for use in gait rehabilitation robot.