

Force/Torque Sensorless Impedance Control for Indirect Driven Robot-Aided Gait Rehabilitation System*

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Abstract— Robot gait rehabilitation has been emerging as an important training technique for patients whose ability to walk is impaired. The “patient-cooperative” approaches are able to detect patient’s voluntary efforts and allow patients to actively influence a gait pattern during rehabilitation processes. The impedance control method is a key technique of “patient-cooperative” strategies that allows deviating desired trajectories by sensing interaction torque. This paper introduces an indirect drive gait training rehabilitation robot system which composed of timing belt and harmonic drive transmissions. We present compensation methods and investigate reaction torque observer (ROB) for estimating patient/robot interaction torque and its application in force/torque sensorless impedance control of patient-cooperative strategy in gait rehabilitation.

I. INTRODUCTION

Recently, a number of robotic gait training systems have been widely developed for helping or saving time and efforts of therapists: PAM & POGO [1], T-WREX [2], the Gait Trainer [3], Lokomat [4], and ALTACRO [5]. One of deficiency of these devices, however, is that patient’s legs move passively along a predefined trajectory without actively influence their movements. Therefore, various *patient-cooperative* (or assist-as-needed) control techniques have been proposed [6]–[17]. When patients can walk more actively, the feeling of success motivates them and improves the training progress [18]. In implementing the *patient-cooperative* control strategy, impedance control approaches can make deviations from desired trajectories by adding *compliance* to the devices [13]–[17]. The impedance control is implemented with sensing patient’s reaction force/torque. Unfortunately, force/torque sensors increase the cost and complexity of the system hardware. Another drawback of force sensors is that many force/torque sensors are needed to measure external torques at many points of interaction (for example a ground reaction force sensor can only measure ankle/ground interaction force [14]). For that reason, several force sensors are required to be mounted on robot orthosis at locations where human legs attached to robot orthoses [13] in order to sense whole patient/orthosis inter-

action torque. One alternative is to utilize joint torque sensors [19], but cost increase problem still remains.

A method of replacing force/torque sensor hardware with inexpensive software is to estimate external torque by using Reaction Torque Observer (ROB) that had been proposed by Ohnishi [21]. The basic idea of ROB is solving the robot’s dynamics equation for external forces/torques by using command torque and robot’s motion information (position, velocity, and acceleration). ROB has been widely applied in force control and impedance control of industrial robots both with direct drive actuators [20], [21], [22] and indirect drive actuators [23], [24], as well as force control of a wearable exoskeleton [25]. ROB, however, has not been utilized in impedance control of real commercial version of gait rehabilitation robots for *patient-cooperative* strategy. The primary challenge of sensorless impedance control in real systems is that it requires very accurate robot orthoses dynamics and very accurate compensation of friction and gravity effects for accurate estimation of external forces/torques.

In this paper, a real commercial version of robot-aided gait rehabilitation system, Walkbot, is introduced for testing the ROB with indirect drives and adjustable link lengths. Compared to other gait rehabilitation system in term of actuation system, such as: pneumatic cylinders in PAM and POGO [1]; Bowden cable driven series elastic actuators in LOPES [11]; pneumatic muscle actuators in HuREx [7]; DC motor with a ball screw mechanism in Lokomat [4]; and linear motor with lever in ALEX [6], Walkbot is equipped with AC servo motors, and harmonic drive and timing belt transmissions which permit the use of low-torque high-speed motor and more compact in design. In order to implement the ROB, we firstly present friction and gravity compensations which considers nonlinear joint friction effects and adjustable robot’s configuration.

The contribution lies in the application of the ROB for force/torque sensorless impedance control of a commercial version gait rehabilitation robot. For this, we first verify the ROB in a two degrees-of-freedom lab prototype that has almost the same hardware with one two degrees-of-freedom leg of the rehabilitation robot prior to implement in real Walkbot. In addition, some discussions are made on how the ROB can be applied in patient-cooperative strategy in the gait rehabilitation system.

This paper is structured as follows. In section II, we briefly introduce an indirect drive rehabilitation system, and experimental results of the friction and gravity compensation methods that had been applied in the real Walkbot. In section III, we present the ROB structure based on inverse dynamics for estimating patient/robot orthosis interaction torque. In addition, we present a force/torque sensorless impedance

* This work was partially supported by the Technology Innovation Program (10049003) funded By the Ministry of Trade, Industry & Energy (MI, Korea).

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Fig. 1. Walkbot_S Rehabilitation System (picture courtesy of P&S Mechanics Co., Ltd.)

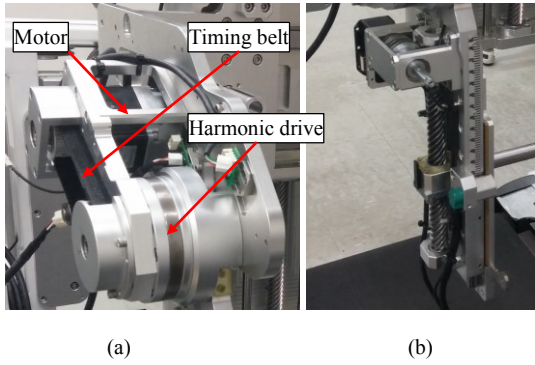


Fig. 2. Walkbot mechanisms. (a) Indirect drive actuator with harmonic drive and timing belt. (b) Adjustable link's length mechanism.

control in joint space by using the ROB, and discuss its application in gait rehabilitation. Section IV illustrates experimental results carried out in a lab prototype. Finally, Section V contains conclusions and future works.

II. AN INDIRECT DRIVE REHABILITATION SYSTEM AND COMPENSATION METHODS

A. Walkbot Rehabilitation System

Fig. 1 shows a robot-aided treadmill training rehabilitation system, Walkbot. The system includes two leg orthoses, an automatic treadmill, Gravity balancing orthosis (GBO) and body-weighted support (BWS) devices, and patient's monitoring displays. The leg orthosis is a two degree-of-freedom robot manipulator with one additional ankle part. Two joints are actuated by AC servo motors, each motor is connected to orthosis's link via a timing belt and a geared reduction harmonic drive (Fig. 2(a)).

The Hip's and Knee's link lengths can be adjustable so that Walkbot is more flexible with variety of patient's limb lengths. Since each link has two mass segments connected via a rack and pinion gear mechanism (Fig. 2 (b)), this mechanism allows two segments to move relatively and as a result adjusts the length of the link.

B. Friction and Gravity Compensation

1) *Friction Compensation*: Hip and Knee actuators are disassembled from Walkbot's exoskeleton for friction measurement procedure. We measured friction torques at hip and

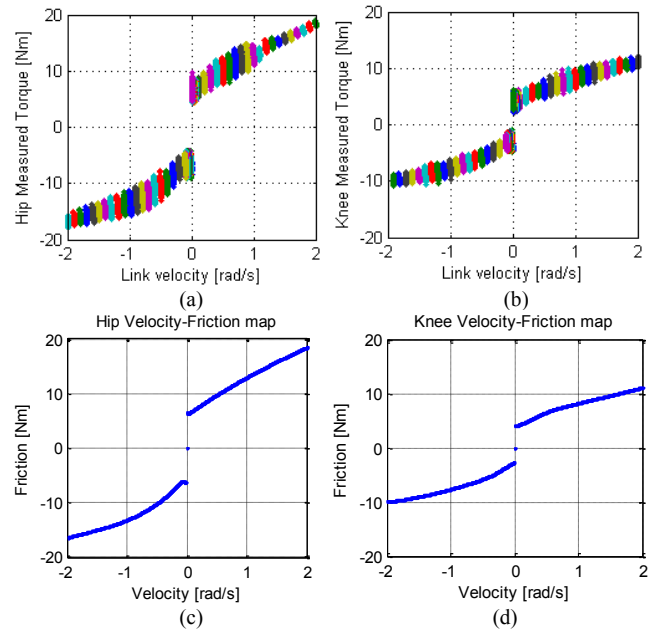


Fig. 3. Walkbot Hip and Knee friction. (a) Hip measured friction torque. (b) Knee measured friction torque. (c) Hip friction fitting curve. (d) Knee friction fitting curve.

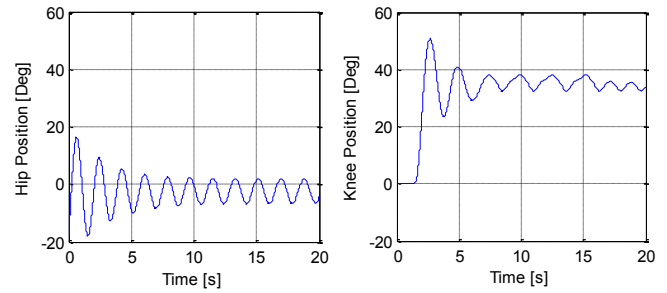


Fig. 4. Hip and Knee angles in Walkbot's friction validation tests

knee actuators at constant velocity mode from a various velocity profiles. A modified exponential friction curve is used to fit the average value of experimental friction data as shown in Fig.3 (c) and (d) [27]. Friction model parameters are obtained by "fminsearch" function in the Optimization Toolbox of MATLAB.

2) *Gravity Compensation*: The gravity compensation method is based on the distribution of the robot segment's masses due to the changeable of link lengths. The segment's weights and their geometric data are obtained from the CAD data of Walkbot. The total potential energy of whole robot orthosis due to the distribution of masses can be obtained as:

$$P = \sum_i m_i g h_i \quad (1)$$

where m_i denotes mass of the i -th segment, h_i is its height with respect to Hip's joint, and g is the gravity acceleration. The gravity torque can be computed as partial differentiation of total potential energy [26]

$$g_i = \frac{\partial P}{\partial q_i} \quad (2)$$

where q_i ($i = 1, 2$) denotes the i -th joint angle.

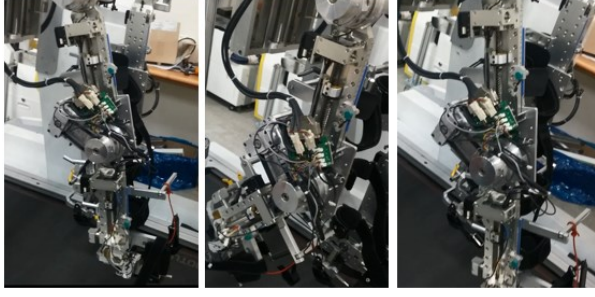


Fig. 5. Gravity compensation validation test on the real Walkbot

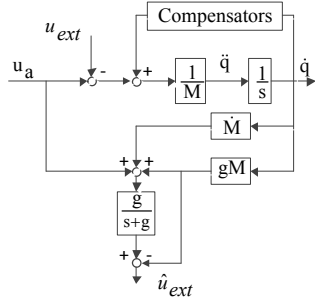


Fig. 6. ROB based on inverse dynamics problem

To validate the friction compensation at the real Walkbot, Hip and Knee moved freely under gravity force after they were released at certain angles, successively. More specifically, during Hip friction validation test, Knee was fixed at its zero angle and whole robot moved around Hip's zero angle. Whereas, during Knee friction validation test, Hip is fixed at a certain positive angle and Knee is freed from its zero angle. Robot's links moved around their balanced position as illustrated in Fig. 4.

If the friction compensation is perfect, robot links should move around forever. However, practically, it is not easy to achieve it. In our experiments, joint angles converge to their balanced angles since friction torque is not perfectly compensated and potential energy is dissipated by heat transformation and air resistance (Fig. 4).

When friction and gravity torque are compensated, the robot is able to maintain its poses. Fig. 5 shows different gestures of Walkbot when whole compensators are activated.

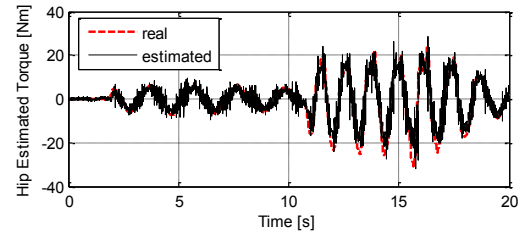
III. REACTION TORQUE OBSERVER AND FORCE/TORQUE SENSORLESS IMPEDANCE CONTROL

A. Reaction Torque Observer (ROB)

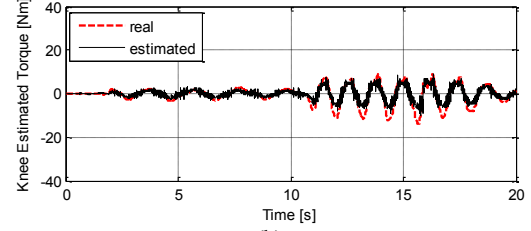
One leg of Walkbot can be modelled as a double pendulum and the dynamic equation of a 2-DOF robot manipulator is in the form [26]

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{f}(\mathbf{q}) + \mathbf{g}(\mathbf{q}) + \mathbf{u}_{ext} = \mathbf{u} = \mathbf{R}\boldsymbol{\tau}_m \quad (3)$$

where $\ddot{\mathbf{q}}$, $\dot{\mathbf{q}}$, and $\mathbf{q} \in \mathbb{R}^2$ are joint space acceleration, velocity and position vectors, respectively. $\mathbf{M}(\mathbf{q}) \in \mathbb{R}^{2 \times 2}$ is the inertia matrix, $\mathbf{C}(\mathbf{q}, \dot{\mathbf{q}}) \in \mathbb{R}^{2 \times 2}$ is the Coriolis and centrifugal matrix, $\mathbf{f}(\mathbf{q})$ and $\mathbf{g}(\mathbf{q})$ are the friction and the gravity vector effects, $\mathbf{u}_{ext}$ denotes the interaction torque between patient's leg and orthosis, $\mathbf{R} \in \mathbb{R}^{2 \times 2}$ is the diagonal gear ratio



(a)



(b)

Fig. 7. ROB performance in Walkbot, filter cutoff frequency $g=10\pi$ rad/s. (a) Hip estimated external torque. (b) Knee estimated external torque.

matrix, and $\mathbf{u}$ and $\boldsymbol{\tau}_m \in \mathbb{R}^2$ are the control torque in load-side and equivalent control torque in the motor-side, respectively.

In the compensated mode, robot manipulator is compensated for friction torque, gravity torque, and Coriolis and centrifugal torque. The control torque based on inverse dynamics is then represented as

$$\mathbf{R}\boldsymbol{\tau}_m = \mathbf{u} = \mathbf{u}_a + \widehat{\mathbf{f}}\mathbf{r}(\dot{\mathbf{q}}) + \widehat{\mathbf{g}}(\mathbf{q}) + \widehat{\mathbf{C}}(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}} \quad (4)$$

where, $\widehat{\mathbf{f}}\mathbf{r}(\dot{\mathbf{q}})$ denotes the estimated terms, and $\mathbf{u}_a$ is commanded torque actually applied to compensated plant.

Replacing control torque in (4) into (3) and solving for external torque $\mathbf{u}_{ext}$, with perfect compensation assumption, we have

$$\mathbf{u}_{ext} = \mathbf{u}_a - \mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} \quad (5)$$

Equation (5) illustrates the estimation of external torque as a dynamics problem. In real implementation, angular acceleration is obtained by numerical differentiation of angular position. As a result, making torque estimation is highly noisy. Therefore, a low pass filter is usually implemented to reduce noises. We can derive then the ROB equation as

$$\widehat{\mathbf{u}}_{ext} = \frac{g}{s+g}(\mathbf{u}_a - \widehat{\mathbf{M}}(\mathbf{q})s\dot{\mathbf{q}}) \quad (6)$$

where g is the cutoff frequency of lowpass filter.

Equation (6) can be written as the following implementation equation and its derivation is illustrated in the Appendix. The block diagram of ROB is shown in Fig. 6.

$$\widehat{\mathbf{u}}_{ext} = \frac{g}{s+g}(\mathbf{u}_a + g\widehat{\mathbf{M}}(\mathbf{q})\dot{\mathbf{q}} + \dot{\widehat{\mathbf{M}}}(\mathbf{q})\dot{\mathbf{q}}) - g\widehat{\mathbf{M}}(\mathbf{q})\dot{\mathbf{q}} \quad (7)$$

Fig. 7 depicts the feasibility of the ROB when robot orthosis is moved by human hand in compensated mode. Estimated torque is compared with real external torque measured by a 6 axis force/torque ATI Nano 25. The sensor is attached at ankle part. However, we can see that these estimated torques are under estimated due to remaining uncompensated friction and other uncertainties.

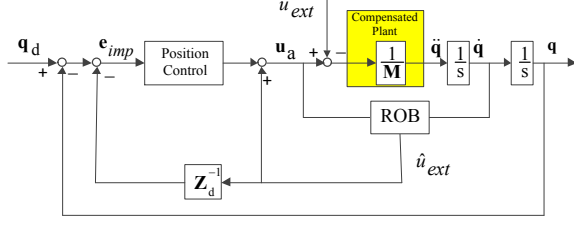


Fig. 8. Torque sensorless position-based impedance control in joint space

B. Force/Torque Sensorless Impedance Control

The concept of impedance control was firstly proposed by Hogan [28]. Since position-based impedance control is more suitable for indirect driven robot manipulator as providing stable and precise motion control [29], it is selected for our control algorithm.

The position-based impedance control (PBIC) law in joint space is given by:

$$\mathbf{u} = \hat{\mathbf{M}}(\mathbf{q})\mathbf{a}_q + \hat{\mathbf{u}}_{ext} + \hat{\mathbf{C}}(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}} + \hat{\mathbf{f}}\mathbf{r}(\dot{\mathbf{q}}) + \hat{\mathbf{g}}(\mathbf{q}) \quad (8)$$

where $\hat{\mathbf{u}}_{ext}$ is estimated external torque from ROB. The acceleration term $\mathbf{a}_q$ takes the following form:

$$\mathbf{a}_q = \ddot{\mathbf{q}}_d + \mathbf{K}_p \mathbf{e}_{imp} + \mathbf{K}_v \dot{\mathbf{e}}_{imp} \quad (9)$$

$$\mathbf{e}_{imp} = \mathbf{q}_d - \hat{\mathbf{u}}_{ext} \mathbf{Z}_d^{-1} - \mathbf{q} \quad (10)$$

$$\dot{\mathbf{e}}_{imp} = \dot{\mathbf{q}}_d - \hat{\mathbf{u}}_{ext} \mathbf{S} \mathbf{Z}_d^{-1} - \dot{\mathbf{q}} \quad (11)$$

where $\mathbf{q}_d$ denotes desired position, $\mathbf{e}_{imp}$ and $\dot{\mathbf{e}}_{imp}$ denote the impedance error and its first derivative. $\mathbf{K}_v$ and $\mathbf{K}_p \in \mathbb{R}^{2 \times 2}$ denote the diagonal derivative and proportional controller's gain matrices, $\mathbf{Z}_d = \mathbf{M}_d s^2 + \mathbf{B}_d s + \mathbf{K}_d$ denotes the desired impedance model. In (10) and (11), feedback of the estimated torque results in the deviations of reference angular position and velocity. The overall diagram of the force/torque sensorless position-based impedance control algorithm is shown in Fig. 8.

IV. EXPERIMENTAL RESULTS

The force/torque sensorless impedance control was implemented on a 2-DOF indirect driven manipulator, a lab prototype of Walkbot, which has the same leg as Walkbot's specification but with fixed link lengths and no ankle. The specification of the robot is shown in Table 1. A 6 axis force/torque ATI Nano 25 was attached on the end effector to verify the performance of ROB as illustrated in Fig. 9.

The desired impedance model parameters are chosen as in Table 2 by selecting natural frequency ω and damping ratio ζ . The PD gains were selected same both for Hip and for Knee as in (12). The cutoff frequency of lowpass filters of ROB in both joints are $g=6\pi$ (rad/s).

$$\mathbf{K}_p = \begin{bmatrix} 750 & 0 \\ 0 & 750 \end{bmatrix} \text{ (Nm/rad)}$$

$$\mathbf{K}_v = \begin{bmatrix} 100 & 0 \\ 0 & 100 \end{bmatrix} \text{ (Nms/rad)} \quad (12)$$

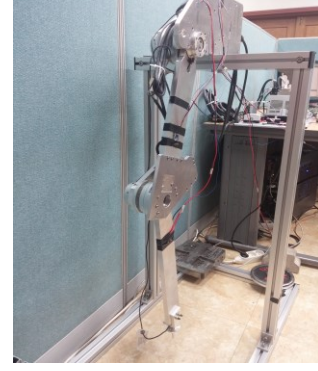


Fig. 9. 2-DOF indirect drive manipulator

TABLE I. 2-DOF MANIPULATOR SPECIFICATION

	<i>Hip</i>	<i>Knee</i>
Gear ratio	150:1	120:1
Servo motor	AC Servo motor	AC Servo motor
Encoder resolution	2048 pulse/rev	2048 pulse/rev
Range of movement	-25.5~37.5°	0~64°

TABLE II. IMPEDANCE PARAMETERS

Link	Parameters		
	M_d (kgm ²)	B_d (Nms/rad)	K_d (Nm/rad)
Hip	2.0	$2\zeta_H \omega_H \sqrt{M_d}$	$(\omega_H)^2 M_d$
Knee	2.0	$2\zeta_K \omega_K \sqrt{M_d}$	$(\omega_K)^2 M_d$

We conducted the PBIC with ROB experiments for two cases: first with soft impedance model, i.e. $\omega_H = \omega_K = 1.8\pi$ rad/s and $\zeta_H = \zeta_K = 0.7$ (Fig. 10); and second with stiff impedance model, i.e. $\omega_H = \omega_K = 6.0\pi$ rad/s and $\zeta_H = \zeta_K = 0.7$ (Fig. 11). In both cases, human efforts can influence reference trajectories resulting in deviations of desired position during interaction mode. In the meantime, the control strategy guarantees good position tracking performance in free space (no exerted torque). In the first experiment, human can easily deviate reference joint positions with small applied torque (Fig. 10). On the contrary, he/she might need high interaction torques to affect the reference joint positions (Fig. 11) when the desired impedance is stiff. However, the latter case has lower impedance error and better position tracking in free space. Note that when the desired impedance model is soft, uncompensated remaining friction and other uncertainties degrade the performances of PBIC. Note also that, in our experiments, these remaining friction and uncertainties cause some fluctuations in actual leg position if the desired impedance model is too soft. When the desired impedance model is too stiff, the PBIC controller acts as a simple position controller.

In real practice of the aforementioned force/torque sensorless position-based impedance control of the commercial version gait rehabilitation robot, a patient's weight is partly supported by Walkbot's weight-supported devices and patient/robot orthosis interaction torque is estimated by ROB when the human is wearing the orthosis. Therapists may

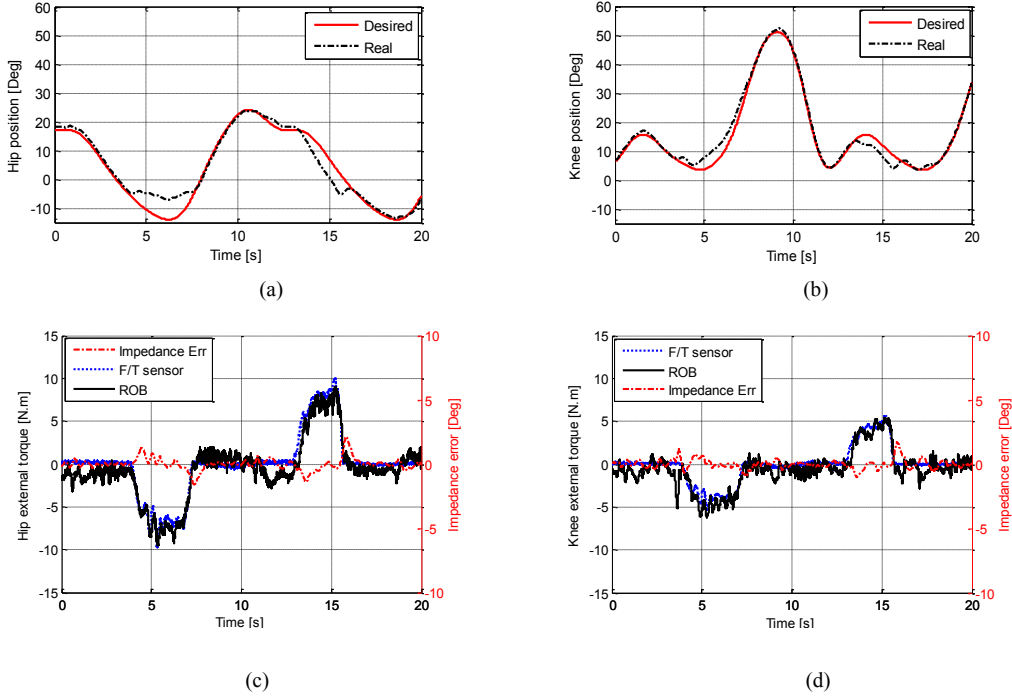


Fig. 10. Torque sensorless impedance control with soft impedance model. (a) Hip joint angle. (b) Knee joint angle. (c) Hip estimated torque and impedance error. (d) Knee estimated torque and impedance error.

choose impedance parameters depend on targeted patients whether they want robot orthosis is flexible or stiff. We may set a deadband or limited threshold of angle's deviation ($\hat{\mathbf{u}}_{ext} \mathbf{Z}_d^{-1}$) in (10) for guaranteeing that patient's legs will not move too far from the reference position similar to the principle of virtual tunnel [9]. Patients will be forced to move back within the tunnel when they are at the boundaries of the tunnel. The above control strategy, however, when applied in real Walkbot, may need a great deal of experiments with human subjects in order to verify its reliability.

V. CONCLUSION

This paper introduced a newly developed indirect drive gait rehabilitation system Walkbot. We presented experimental results of friction and gravity compensation methods showing the effectiveness of compensations. The following position-based impedance control using the ROB validated that the sensorless impedance control in a lab prototype robot can be applied in real commercial version system. The control strategy is simple in implementation and its effectiveness is shown in our experiments.

In future works, we intend to apply the force/torque sensorless impedance control in real Walkbot system and carry out experiments on human subjects. Furthermore, rigorous stability and convergence analyses of the control law are also our future research.

APPENDIX

The derivation of (7) from (6).

Since, $s\hat{\mathbf{M}}(\mathbf{q})\dot{\mathbf{q}} = \dot{\hat{\mathbf{M}}}(\mathbf{q})\dot{\mathbf{q}} + \hat{\mathbf{M}}(\mathbf{q})s\dot{\mathbf{q}}$ we have:

$$\begin{aligned}
 (6) = \hat{\mathbf{u}}_{ext} &= \frac{g}{s+g} [\mathbf{u}_a - \hat{\mathbf{M}}(\mathbf{q})s\dot{\mathbf{q}}] = \frac{g}{s+g} [\mathbf{u}_a - \\
 & (s\hat{\mathbf{M}}(\mathbf{q})\dot{\mathbf{q}} - \dot{\hat{\mathbf{M}}}(\mathbf{q})\dot{\mathbf{q}})], \\
 &= \frac{g}{s+g} [\mathbf{u}_a - s\hat{\mathbf{M}}(\mathbf{q})\dot{\mathbf{q}} + \dot{\hat{\mathbf{M}}}(\mathbf{q})\dot{\mathbf{q}}] = \frac{g}{s+g} [\mathbf{u}_a - \\
 & (s+g)\hat{\mathbf{M}}(\mathbf{q})\dot{\mathbf{q}} + g\hat{\mathbf{M}}(\mathbf{q})\dot{\mathbf{q}} + \dot{\hat{\mathbf{M}}}(\mathbf{q})\dot{\mathbf{q}}] = \\
 &= \frac{g}{s+g} (\mathbf{u}_a + g\hat{\mathbf{M}}(\mathbf{q})\dot{\mathbf{q}} + \dot{\hat{\mathbf{M}}}(\mathbf{q})\dot{\mathbf{q}}) - g\hat{\mathbf{M}}(\mathbf{q})\dot{\mathbf{q}} = (7).
 \end{aligned}$$

ACKNOWLEDGMENT

Authors would like to thank P&S Mechanics Co., Ltd. for cooperating work and for providing data on the Walkbot.

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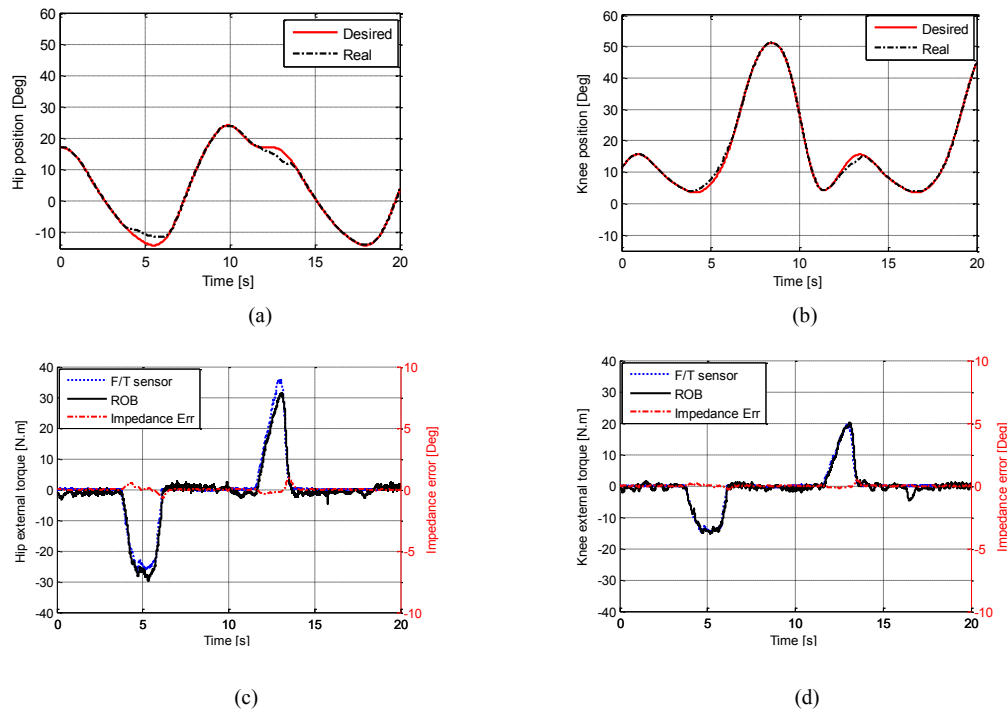


Fig. 11. Torque sensorless impedance control with stiff impedance model. (a) Hip joint angle. (b) Knee joint angle. (c) Hip estimated torque and impedance error. (d) Knee estimated torque and impedance error.

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