Intentional Movement Performance Ability (IMPA): A Method for Robot-Aided Quantitative Assessment of Motor Function

Sung Yul Shin, Jung Yoon Kim, Sanghyeop Lee, Junwon Lee, Seung-Jong Kim and ChangHwan Kim

Abstract— **The purpose of this paper is to propose a new assessment method for evaluating motor function of the patients who are suffering from physical weakness after stroke, incomplete spinal cord injury (iSCI) or other diseases. In this work, we use a robotic device to obtain the information of interaction occur between patient and robot, and use it as a measure for assessing the patients. The Intentional Movement Performance Ability (IMPA) is defined by the root mean square of the interactive torque, while the subject performs given periodic movement with the robot. IMPA is proposed to quantitatively determine the level of subject's impaired motor function. The method is indirectly tested by asking the healthy subjects to lift a barbell to disturb their motor function. The experimental result shows that the IMPA has a potential for providing a proper information of the subject's motor function level.**

I. Introduction

For the past decades, the application of robotics in rehabilitation area has been used to treat and evaluate the patients who have impairments in motor function after stroke, incomplete Spinal Cord Injury (iSCI) or other diseases. Compared to the conventional manual rehabilitation therapies, the robotic rehabilitation may have some advantages such as 1) reducing the physical burdens on the clinical therapists, 2) quantitatively assessing the patients with the information acquired from the various sensors and 3) assisting the repetitive training with an appropriate purpose [1], [2].

The MIT-MANUS, MIME (mirror image movement enhancer) and ARM Guide represent early advances of rehabilitation robot, which are used for clinical neurological application [3]-[6]. A number of upper extremity rehabilitation robots have been developed in the last few years for improving motor recovery in patients with neurological or orthopaedic lesions. ARMin is a robot for arm therapy applicable to the training of activities of daily living in clinics [7]. CAREX (a Cable Driven ARm EXoskeleton) is a newly developed cable driven upper extremity robot, which enables to achieve forces in all directions at the wrist with the cables, driven by the motors [8]. Several lower extremity rehabilitation robots are also developed for gait training during walking. Lokomat and ALEX (Active Leg EXoskeleton) are the gait rehabilitation exoskeletons on a treadmill developed to assist patients with movement disorders while walking [1], [2], [9]. The extensions of the passive gait training are the patient-cooperative control strategies, which are applied to encourage the patients to actively participate in the training by using virtual tunnel or force field controller [1], [2], [10]. While the robot-assisted training is playing an important role in the rehabilitation area [1]-[10], the robot-exploited assessment of patients may be another key advantage since the robots are well suited for dealing with the physical motion and force and have various sensors that may provide quantitative information [1].

The widely accepted standard assessment procedures for muscle strength include manual muscle testing using Medical Research Council (MRC) scale and measurement using dynamometer [14]-[16]. Furthermore, functional limitations are usually quantified using clinical evaluation scales such as Functional Independence Measure (FIM) and Fugl-Meyer Assessment (FMA) scale [11]-[13]. FIM is a scale to measure the physical and cognitive disability of the patients [11], [12]. Items are scored on the level of assistance required for a patient to perform the functional tasks of daily living, such as eating or dressing. FMA is a scale that measures the upper extremity and lower extremity motor and sensory impairments [13]. These assessment procedures are practically used in rehabilitation hospitals, and even used as the assessment measure after the robotic training [4]. Although these standard assessment procedures are broadly applied in clinical practice, the results may be comparatively subjective since the factors such as clinician's experience or personality may affect the evaluation. In addition, the score does not sufficiently subdivide the patient's level, but only discretizes the patient groups into a few levels. For example, FIM and MRC scale for muscle strength are graded on a scale from 1 to 7 and 0 to 5, respectively; these may categorize the patients with different motor function level into same group.

In this paper, we introduce a simple method for quantitatively assessing the patients' motor function level by exploiting a robotic device. The sensors attached on the robot provide the data that can be used to quantitatively evaluate and subdivide the patient groups. One of the robotic devices that provides the quantitative data is the isokinetic dynamometer such as the Biodex system IV dynamometer, which provides assessments of dynamic and also static muscle strengths by measuring the torque [15], [16]. However, even though the muscle strength is the fundamental source for making body movements, it does not accurately reflect the motor function derived from the patient's intentional

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movement. One of the most important issues in physical rehabilitation is retraining the motor coordination and the muscle strength, therefore the measure of the motor function would be an important element when assessing a patient [19]-[21]. We propose *Intentional Movement Performance Ability* (IMPA), which is a scale that measures how well the patient can perform his/her intended movement. Before the testing, the patient is instructed to follow the periodic movement of the robot while wearing it, and the interactive torque occur between robot and patient is measured and used as the scale of the IMPA.

More details about the IMPA is described in Sec. II, the derivation of the interactive torque and the specifications of the system used for the experiment are explained in Sec. III and Sec. IV, respectively. The experimental results, discussion and the conclusion are followed in Sec. V, Sec. VI and Sec. VII, respectively.

II. Intentional Movement Performance Ability

The main goal of the physical therapy is to assist the patients to regain the use of impaired limbs. Retraining of motor function by performing repetitive and concentrative exercise is the most significant element of the physical rehabilitation [1], [19]-[21]. Therefore, the quantitative scale of the motor function would be a useful information when evaluating a patient's level of recovery.

IMPA is a scale that measures the intentional movement performed by a subject. The conceptual picture of the IMPA measuring procedure is illustrated in Fig. 1. The subject is instructed to follow the movement of the robot, while the subject's limb is strictly attached to the robot arm. The periodic movement of the robot arm is operated in position control mode. The position control means that the robot always exerts to follow the given target trajectory, even though the robot is perturbed by the external forces applied by the subject. If the robot starts to move, the subject will sense the interactive force applied on the limb, and this sensory feedback will activate the subject's brain to trigger the motor control. Consequently, the muscle contraction will lead the subject to actuate the movement for following the robot. This process will be continuously repeated during the testing period (see Fig. 1).

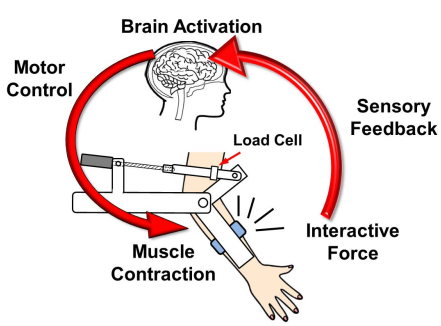

Fig. 1. Conceptual picture of the IMPA measuring procedure. The interactive torque between human and robot is obtained by using the measured force from the load cell.

Therefore, the subject's goal is to follow the trajectory of the robot with minimum help of robot's assistance during the testing period. Ideally, if the subject is able to move exactly same as the movement of the robot with his/her own strength (which would be almost impossible even with the healthy subjects), the interactive force between the subject and the robot will be zero. Indeed, the healthy subjects without any impairments in motor function will have the interactive force almost close to zero. On the other hand, the patients with significant muscle weakness or impaired motor coordination will have larger interactive force compared to the healthy subjects. The idea is to quantify the subject's motor function level by using the amount of interaction occur between the subject and the robot. Therefore, physically, IMPA is defined by the root mean square (RMS) of the interactive torque, while the subject follows the given periodic movement of the robot as follows:

$$\tau_{IMPA} = \sqrt{\frac{1}{T_f}\int_0^{T_f} [\tau_{int}(t)]^2 dt} \tag{1}$$

where τ_{IMPA} is the value of IMPA; $\tau_{int}(t)$ is the interactive torque and T_f is the time range of testing period.

In the following section, we explore how we obtain the interactive torque with a simplified human-robot interactive system.

III. Human-Robot Interactive System

One of the most important issues in rehabilitation robot is the interaction between robot and human since the robot is not solely controlled by itself, but it continuously cooperates with the human during the operation [17]. In this section, we deal with the human-robot interactive system to obtain the interactive torque. For better understanding, we simplify the system into a one translational dimension as shown in Fig. 2. Since the rotary system is simplified into a translational system, the interactive torque can be substituted with the interactive force. The whole system consists of 1) a robot actuator, 2) a robot mass, 3) a human actuator, 4) a human mass, and a load cell, the sensor that measures the force applied on the system, is placed between the robot actuator and the robot mass as shown in Fig. 2.

By assuming that the robot and the human are strictly attached together, the net force, F_{NET} applied on the system can be expressed as

$$F_{NET} = F_R - F_H = (m_R + m_H)\ddot{x} \tag{2}$$

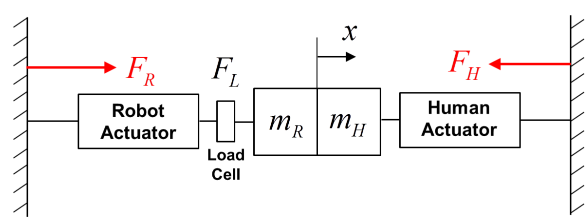

Fig. 2. The simplified human-robot interactive system in one dimension.

where F_R is the force generated by the robot actuator; F_H is the force generated by the human actuator; m_R is the robot mass; m_H is the human mass and $\ddot{x}$ is the measurable acceleration. Since the load cell is placed between the robot actuator and the robot mass, the measured force, F_L is given by

$$F_L = F_R = F_H + (m_R + m_H)\ddot{x}. \tag{3}$$

The interactive force can be defined as the pure force applied on the robot by the human [10]. Therefore, the interactive force, F_{int} can be expressed as

$$F_{int} = F_H + m_H\ddot{x}. \tag{4}$$

Physically, the first term, F_H can be interpreted as the active force generated by the human muscles and the second term, $m_H\ddot{x}$ can be interpreted as the inertial force generated by the mass of the human limb. This means that if the human totally relaxes his/her limb muscles ($F_H = 0$), the human limb can be simply considered as a mass. Finally, by combining (3) and (4), and rearranging them, the interactive force can be obtained as follows:

$$F_{int} = F_L - m_R\ddot{x}. \tag{5}$$

The interactive force can be replaced with the interactive torque, if the translational system alters to the rotary system. In general, the robot model, which is $m_R\ddot{x}$ in (5) for our simplified model, can be calculated by using the dynamic equation of motion of the system. In our actual system, the interactive torque is calculated by using the measured force from the load cell, and used to obtain the IMPA value with (1).

IV. SYSTEM

A. Structure and Mechanism

In this subsection, we describe the robotic system that we developed for the experiment. A one degree-of-freedom (DOF) robotic device, Assistive Training Orthosis (ATO) is implemented to test our proposed assessment method, IMPA (see Fig. 3) [22]. The structure and mechanism of the system are shown in Fig 4. The system consists of largely 4 parts (L1-L4 in Fig. 4); L1: the motor and ball screw part, L2: the link that contains the slide nut and load cell, L3: the orthotic link and L4: the support part. The ball-screw type linear joint is employed to rotate the orthotic link. To measure the force applied on the system, the 1-axis load cell is attached between the linear joint part (L2) and the orthotic link (L3). The kinematic and dynamic formulations of the system are solved to determine the required speed and torque for operating the system, and the resultant design specification is denoted in Table I [22]. More details of the system design is presented in [22].

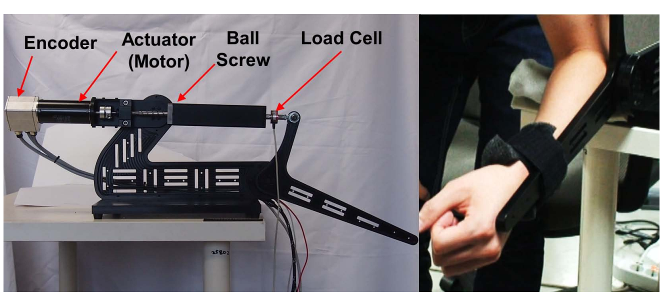

Fig. 3. The left figure is the 1-DOF robotic system, ATO developed in Korea Institute of Science and Technology (KIST) and the right figure shows a subject's arm attached with ATO to measure IMPA.

TABLE I
DESIGN SPECIFICATION OF THE SYSTEM

Orthotic Joint Range	0 ∼ 70 [deg]
Ball-Screw Stroke	Stroke: 13.27 [cm]
Ball-Screw	MISUMI, BSSR1010 (Lead: 10 [mm/rev])
Motor	Maxon EC45 (136209), (Nominal torque: 323 [mNm], Nominal speed: 5770 [RPM])

B. Real-Time Realization

The xPC package is adopted to translate and compile the MATLAB/Simulink model into a real-time executable program. The program is executed at a sampling time of 1 kHz. The xPC package provides the on-line sampling and off-line representation of the Simulink signals of interest, and also allows to change model parameters in real-time and display different signals of interest. The robot control architecture is implemented in the Simulink model of the host personal computer (PC), and the communication between the host PC and the target PC, which contains D/A, A/D and DIO convertors, is achieved by TCP/IP.

C. Controller

The trajectory tracking control is implemented for the experiment. The conventional proportional-derivative (PD) controller is used to control the robot. The control input is given by

$$u(t) = k_p(\theta_d(t) - \theta(t)) + k_d(\dot{\theta}_d(t) - \dot{\theta}(t)) \tag{6}$$

where $u(t)$ is the control input of the motor; $\theta_d(t)$ is the target joint position of the motor and $\theta(t)$ is the current joint

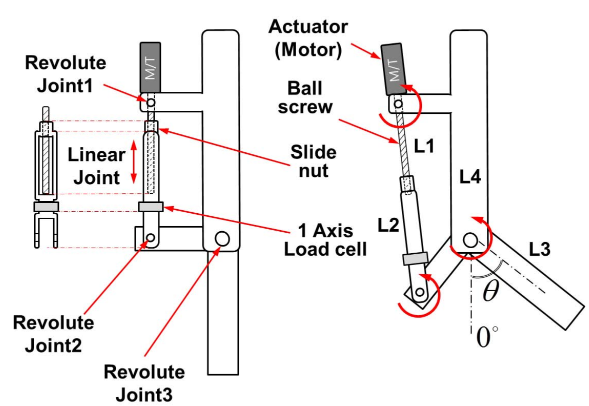

Fig. 4. Structure and mechanism of the 1-DOF robotic system, ATO.

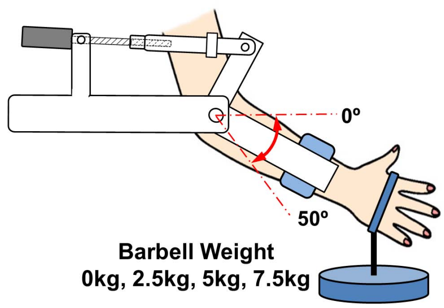

Fig. 5. Schematic picture of the experiment for measuring IMPA.

position of the motor, which is acquired from the encoder. k_p is the proportional gain and k_d is derivative gain: $k_p = 5$, $k_d = 2\sqrt{k_p}$. To control the joint position of the orthotic link, the kinematic formulations are implemented in the control architecture [22].

V. Experiment

A. Experimental Setup

The experiment was conducted to test IMPA. Four healthy subjects (S1-S4) without any motor impairments (4 males, mean age: 31, range: 27-38) volunteered for the experiment. Prior to the experiment, all the subjects were taught what they are going to undergo, and all of them agreed to participate the experiment. Since all the participants were healthy subjects, they were asked to life up a barbell of a certain amount in order to mimic the patients who have impaired upper limb. The 4 weights of barbell, varied from 0kg to 7.5kg (weight: 0kg, 2.5kg, 5kg, 7.5kg), are lifted in this experiment.

As shown in Fig. 5 (also see right picture in Fig. 3), the robot arm and each subject's upper limb was strictly tightened with velcro tape. Before the experiment, the subjects were instructed to follow the movement of the robot. The periodic joint movement of the orthotic link was given by a sinusoidal wave (range: 0°-50°, reference trajectory: $\theta_r(t) = -A\cos\omega t + A$, with $A = 25°$ and $\omega = 1$rad/s, testing period: 1 minute) for the subjects to follow. Each subject performed 4 sessions of the experiments by lifting 0kg, 2.5kg 5kg and 7.5kg barbells, respectively. For each session, the force applied on the system was measured by the load cell, and interactive torque is calculated to obtain the IMPA value.

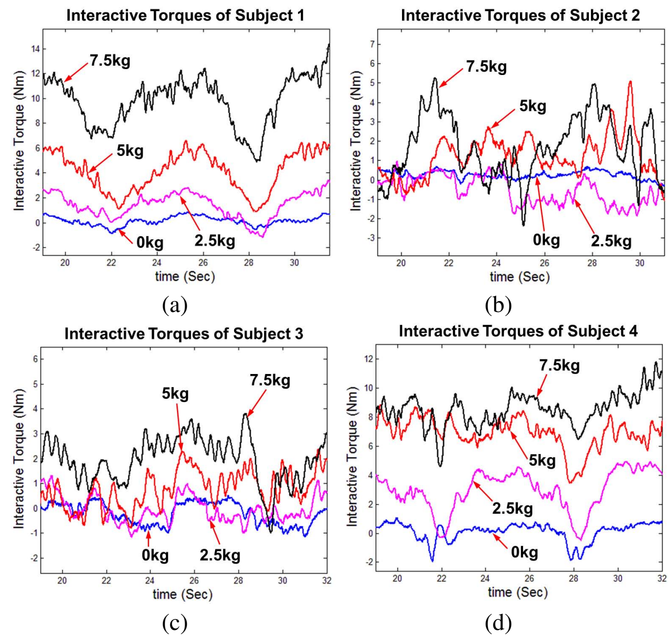

Fig. 7. Interactive torque trajectories in 2 cycle movements (19-32 seconds: between red dotted lines in Fig. 6 (a)) while lifting up 0kg, 2.5kg, 5kg and 7.5kg weights. (a) S1, (b) S2, (c) S3 and (d) S4.

B. Experimental Results

The experiments were performed in trajectory tracking control mode by using the PD controller presented in Sec. IV-C, while the subjects' limbs were attached with the robot arm. The target and current trajectories of the orthotic joint movement for one session period is shown in Fig. 6 (a), and the magnified target and current trajectories inside the red dotted circle in Fig. 6 (a) is shown in Fig. 6 (b). It is observed that the trajectory tracking is successfully performed within maximum error 0.52° (mean error 0.31°). Note that the target and current trajectories of all the subjects have identical shape since the robot was controlled in a position control mode.

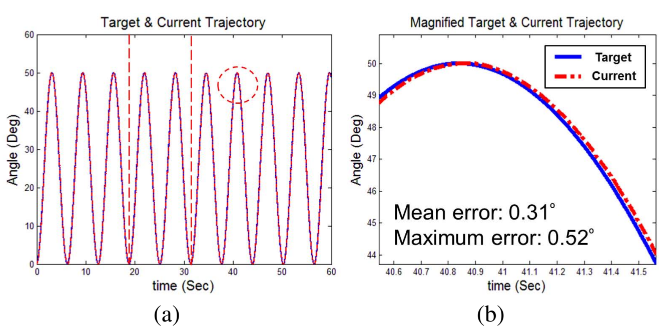

Fig. 6. (a) Target and current trajectories of robot movement given by a sinusoidal wave (range: $0° \sim 50°$, reference trajectory: $\theta_r(t) = -A\cos\omega t + A$, with $A = 25°$ and $\omega = 1$rad/s, testing period: 1 minute) and (b) magnified target and current trajectories inside of the red dotted circle in (a).

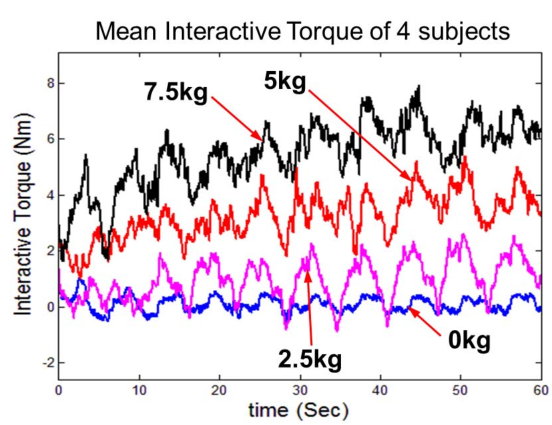

Fig. 8. Mean interactive torque of 4 subjects for a full session (1 minute).

TABLE II
MEAN (±STANDARD DEVIATION) OF THE INTERACTIVE TORQUE

	0kg	2.5kg	5kg	7.5kg
S1 (Nm)	0.05 (±0.41)	1.81 (±1.36)	4.51 (±2.00)	8.69 (±2.32)
S2 (Nm)	0.19 (±0.29)	-0.55 (±0.81)	0.43 (±1.31)	2.09 (±1.80)
S3 (Nm)	-0.14 (±0.62)	0.04 (±0.66)	1.25 (±0.96)	1.82 (±0.98)
S4 (Nm)	0.27 (±0.59)	2.47 (±1.36)	6.65 (±1.36)	9.03 (±2.58)
Mean (Nm)	0.09 (±0.48)	0.94 (±1.05)	3.21 (±1.41)	5.41 (±1.92)

The interactive torques in 2 cycle movements (19-32 seconds: between red dotted lines in Fig. 6 (a)) of S1-S4 are depicted in Fig. 7 (a)-(d), respectively. Each graph involves 4 interactive torque trajectories, while lifting 0kg, 2.5kg, 5kg and 7.5kg barbells, respectively. In addition, the mean interactive torque of 4 subjects in full time range of one session (1 minute) is shown in Fig. 8, and the mean and standard deviation of all subjects and mean interactive torque are denoted in Table II. Lastly, the IMPA value of 4 subjects are obtained by using (1). The IMPA value of 4 subjects (S1: blue circle, S2: magenta diamond, S3: red star, S4: black triangle) and mean of 4 subjects' IMPA value (black cross with dotted line) are shown in Fig. 9.

VI. DISCUSSION

One potential benefit obtainable from the robotic application in rehabilitation is the quantitative assessment of the patients [1], [2], [18]. In this paper, we propose IMPA, a method for assessing the patients' motor function level based on the interaction occur between robot and human. Although our experimental results based on healthy subjects may not accurately model the actual patients, we believe that lifting weights by healthy subjects may reflect the patients' impaired behavioral characteristics and may adequately provide the meaningful information as a pilot study.

In Fig. 7, it can be observed that most of the subjects' interactive torques increase as the weight gets heavier; especially, S1 and S4 (Fig 7. (a) and (d)) show distinct variations in terms of the different weights. Likewise, the mean interactive torque of 4 subjects also increases as the weight gets heavier (see Fig. 8). As expected, the interactive torques of subjects with 0kg weight (healthy subjects) are almost close to zero for the whole session; the mean (±standard deviation) interactive torque of 4 subjects with 0kg weight is 0.09 (±0.48) (see Table II). This means that the healthy subjects are able to follow the movement of the robot with a small amount of interference, whereas the amount of interference gets larger as the weight gets heavier. Furthermore, it can be observed in Fig. 8 that the interactive torque trajectories of subjects with weights slightly increase as the time passes due to the accumulated fatigue from lifting up heavy barbells (the subjects pleaded difficulties in conducting the experiment with heavier than 7.5kg weight); this indicates the testing period is an important factor that influences the IMPA value.

The graphs of the IMPA for 4 subjects and the mean IMPA of 4 subjects are shown is Fig. 9. It can be seen that each of the subject's IMPA graph have different slope, which is caused by different muscle strength of each subject; stronger subjects may have lower slopes, and vice versa. As a matter of fact, the important point that should be noted in the IMPA graph is that the IMPA value increases as the weight gets heavier. This means that the IMPA value increases as the subject's motor function level gets worse, therefore we anticipate that the IMPA value can be used as a quantitative measure to evaluate the patients' motor function level. Moreover, the IMPA measure can be also used for subdividing the patient groups since the method provides a certain value that is given by the testing result of each subject. It may help to judge whether the subject is healthy or not, by comparing the IMPA value of healthy subjects. For example, based on the experiment in this work, the mean IMPA value of 4 subjects with 0kg weight (0.51 (±0.13)) can be used as a threshold for deciding whether the subject is close to healthy or not (more healthy subjects' data would more generalize the threshold value). It may also provide how far the patient deviates from the healthy subjects, and check the patient's status of recovery after the rehabilitation training.

The IMPA value can be also used to determine the control parameters for the robotic training. For example, one of the recent control strategies for gait training are the patient-cooperative control strategies, which are the methods to encourage the patients to actively participate in the training by using virtual tunnel or force field controller [1], [10]. In the literature, it is presented that the bandwidth of the virtual tunnel was designed heuristically based on the experience

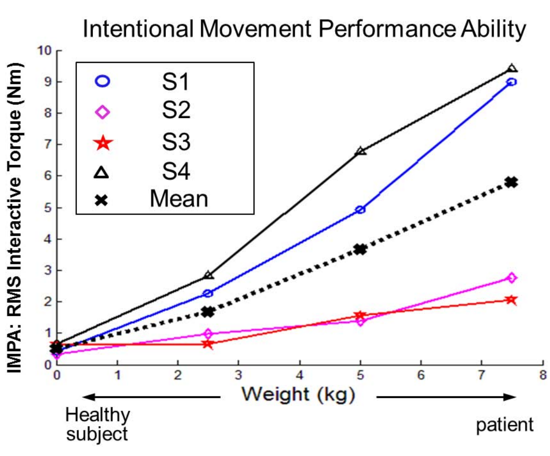

Fig. 9. IMPA of 4 subjects and mean of 4 subjects.

from pre-trials [10]. By using the IMPA, the bandwidth of the virtual tunnel may be automatically adjusted based on the testing result of the patient.

In this work, the experiment was performed with a fixed periodic movement by implementing the 1-DOF robotic system, ATO. However, the IMPA measure can potentially be generalized with the other robots with more DOFs (e.g., [1]-[10]) since the interactive torque for calculating the IMPA value is also obtainable by using their sensors and dynamic equations of motion. Even though we only tested with a fixed periodic movement of the robot due to the limitation of DOFs of our system, assessing the task-oriented movements of daily living such as gait, reaching, grasping or drawing can be also applied by using the high-DOF robots. In this way, the functional limitations may be more quantitatively evaluated compared to the standard assessment measures such as FIM or FMA [11]-[13]; this may provide the clinicians more quantitative information for evaluating patients' motor function for daily living.

In the experiment, the testing period was arbitrarily determined by 1 minute without the initial adaptation time, because the healthy subjects were able to easily adapt to the given periodic movement of the robot. However, these parameter values (range, speed, testing period, adaptation time, etc.) may not be optimal to the actual patients; these parameters may be the significant factors that influence the IMPA result. Thus, appropriate parameter values for the patients should be determined based on the patients' degree of impairment. We are currently collaborating with National Rehabilitation Center (NRC) of Korea to investigate the optimal parameter values for the actual patients.

VII. Conclusion

This paper describes a method for assessing patients who have motor impairments after stroke, iSCI or other diseases. We propose the IMPA, which is a scale that quantitatively measures the intentional movement performance level of a subject by using the interactive torque generated between robot and subject. The 1-DOF robotic device, ATO developed from KIST is used as a test-bed, and 4 healthy subjects were participated in the experiment. The proposed method is indirectly tested with the subjects by lifting a barbell in order to disturb their motor function. The experimental result shows that the IMPA has a potential for quantitatively assessing the subjects' motor function level. In future, we will apply the IMPA to the actual patients in order to investigate whether this method is indeed applicable to them, and find out the optimal parameter values (range, speed, testing period, adaptation time, etc.) for the patients.

VIII. Acknowledgement

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