

A NOVEL DEVICE FOR MEASURING MECHANICAL IMPEDANCE DURING DYNAMIC TASKS

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Abstract: Mechanical impedance is an important factor that the central nervous system takes into account while coordinating a motion. This research work thus aims to develop a new measurement for monitoring dynamic changes of mechanical impedance. The method is introduced and validated in the context. The results show that device correctly measures the dynamic force and impedance of an eccentric linear spring. Furthermore, 62 measurement trails on two human subjects (31 trials on each) confirmed that the value of mechanical impedance changes with adaptation. Finally, we propose a method for the assessment of motor recovery in the stroke patients undergoing rehabilitation sessions.

1 INTRODUCTION

Assessment of human motor function has remained a challenge for years; this is because of the complexity of human brain and the subjective nature of the assessment. On the other hand with its numerous, important applications such as assessment of functional capabilities in post-stroke rehabilitation, motor function assessment undeniably needs improvements and new methods. Although several scoring methods such as Fugl-Meyer (Fugl-Meyer et al, 1975) or NIH stroke scale (Goldstein et al, 1989) already exist, they are generally subjective or qualitative; thus not quite suitable for accurate and scientific studies of motor functions. For clinical purposes, though, these methods are still widely used because of their simplicity. Researchers recently tried to use robots for the assessment besides the physical therapy (Palazzolo et al, 2007) and (Loureiro et al, 2003). Their robots were basically designed for performing physical therapy exercises and because of the capabilities of a robot (Palazzolo et al, 2007) they tried to use the same robot for assessment purposes. Having measured forces with respect to displacement, they measured stiffness of the arm. They assumed a two-DoF model of mass-spring-damper for the arm and tried to estimate stiffness, mass, and damping matrices. However, their method was not a direct, real time, and in-situation measurement. On the other hand, a

robot might be very complicated and expensive; setup and maintenance of it can be very difficult as well. Hence, there still remains a room for a more reliable, convenient, and efficient tool for the assessment of motor function. Furthermore, what the robot measures is also a very important issue for the assessment.

Hogan (Hogan, 1984) showed that the value of mechanical impedance for the upper arm, which is set at the elbow joint, is very important. He examined the postulate that antagonist muscle's co-activation is to generate mechanical impedance and therefore this is necessary to perform some tasks. A typical case with necessity of the antagonist activation is performing a dynamically unstable task. Burdet (Burdet et al, 2001) showed that human learns to stabilize unstable dynamics by optimizing mechanical impedance. Darainy (Darainy et al, 2008) has recently reported that the EMG patterns of dynamic learning reveals a considerable portion of co-activation in mechanically stable tasks. Therefore, this is not only in case of unstable dynamics that the CNS co-contracts the antagonists to control the impedance of the limb, but also in other case of other tasks, with learning the efficient co-activation, it is practically regulating and controlling the mechanical impedance of the limb. Regarding the importance of mechanical impedance and incapability of the conventional methods to measure it, this research aims to develop a novel method for measuring human arm's mechanical

impedance which is usable for the assessment of motor function of patients going under rehabilitation.

2 SENSING CUM ACTUATING

It is known that mechanical impedance is a measure of how much a structure resists motion when subjected to a given force. Hence, in order to measure mechanical impedance, one needs to measure the force and the velocity and calculate the ratio of them.

Measurement of impedance of a limb is usually done using a robot that applies a perturbation to the limb. Then sensors located at the same robot measures the force and the velocity; some notable examples are (Palazzolo et al, 2007), (Burdet et al, 2001), and (Darainy et al, 2008). In general, a robotic device is used so as to measure the force (during motion) and the speed. The two values are then correlated.

Besides the traditional approach discussed above, Ling et al (Ling et al, 2001, 2004, and 2006) have proposed a creative method for impedance. The idea is to make use of simultaneous sensing cum actuating (SSA) property of the electrical motors. Although the method was initially designed for the industrial applications an experimental study (Mousavi et al, 2009) showed that a reversion of it works very well for the medical applications. In this paper, the same method is further modified and then used for measuring arm's mechanical impedance.

According to Figure 1, an electric motor is considered to have four ports: two inputs and two outputs.

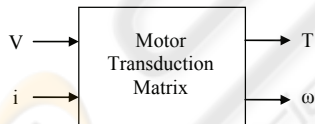


Figure 1: An electromechanical system as a four-pole block.

The input and output are considered two vectors each having two elements. E and I (i.e. voltage and current) are elements of the input vector. T and ω (i.e. torque and angular velocity) are elements of the output vector. The transfer function, relating the input and the output, is a two-by-two matrix which is called Transduction Matrix. As the name suggests, it transfers electrical the entries to the mechanical entries and vice versa.

$$\begin{Bmatrix} E \\ I \end{Bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \times \begin{Bmatrix} T \\ \omega \end{Bmatrix} \quad (1)$$

In order to obtain the transduction matrix T_{ij} we use an experimental procedure to measure E and I while the motor runs at measurable T and ω . Once a number of T and ω versus E and I are attained, matrix T_{ij} is found using least square approximation.

$$\begin{bmatrix} E_1 & \cdots & E_n \\ I_1 & \cdots & I_n \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \times \begin{bmatrix} T_1 & \cdots & T_n \\ \omega_1 & \cdots & \omega_n \end{bmatrix} \quad (2)$$

Using the transduction matrix, we are able to find the mechanical output based on measuring the electrical input. In other words, T and ω are found once E and I are measured.

$$\begin{Bmatrix} T \\ \omega \end{Bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix}^{-1} \times \begin{Bmatrix} E \\ I \end{Bmatrix} \quad (3)$$

Afterwards, mechanical impedance, Z_m , is obtained by dividing ΔT over ω .

$$Z_m = \frac{\Delta T}{\omega} \quad (4)$$

$$\Delta T = T - T_0 \quad (5)$$

Where T_0 is the torque measured at unloaded condition.

3 EXPERIMENTAL STUDY

A typical shoulder wheel, shown in Figure 2, is widely known as a common rehabilitation device. Shoulder wheels are simply found in the market for inexpensive prices and can be installed and used easily. Therefore, prescription of such equipment is welcomed by patients who need physical exercises on their upper limb. These patients normally suffer from muscle atrophy and/or a loss in their ranges of motion. Their practice with a shoulder wheel involves rotating the shoulder wheel while the physiotherapist can adjust the radius of the circular motion. Sometimes they attach some mass blocks to the wheel such that the patient has to apply more torque to rotate and control the wheel. Through the exercise, patients adapt to the motion and their

control over the muscles would improve; hence they recover.

3.1 Apparatus Design

Here, we use a shoulder wheel equipped with a DC motor as the measurement apparatus, shown in Figure 3. The set also involves a current and a voltage probe, and a dynamic signal analyzer, which is depicted in Figure 4.

The set-up was used for measuring human arm's mechanical impedance while the subject was exercising with the shoulder wheel, illustrated in Figure 2.

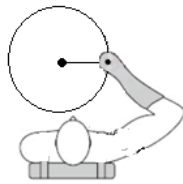


Figure 2: Subject exercising with the wheel.

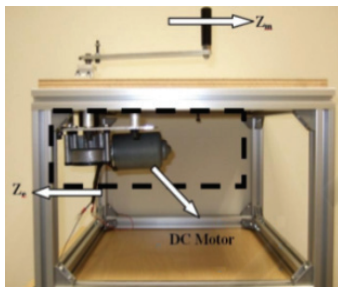


Figure 3: A photograph of the experimental set-up.

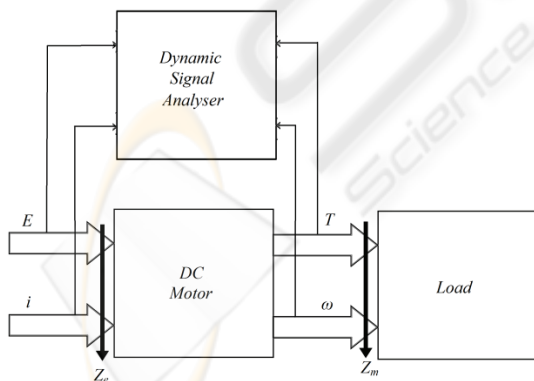


Figure 4: The SSA system in diagram.

Using the apparatuses we have designed, we can measure mechanical impedance of the arm accurately during motion. Study of human motor learning will then be possible; with designing

appropriate experiments, we can examine a number of issues in neuroscience i.e. learning, consolidation, motor forgetting, retention and transfer of tasks. The quantification of motor function provides a very good tool for science and many other applications such as robotics, physical medicine, and physiotherapy.

3.2 Method Verification

To validate the method, before measuring human arm's mechanical impedance, we challenged our method by attaching a linear spring according to Figure 5. The elongation force of the spring generates mechanical impedance that can be measured and compared to an analytical prediction. If the two quantities are comparable, the method is confirmed to be correct. Then we can apply the method to direct measurement of human arm's mechanical impedance.

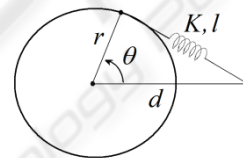


Figure 5: Shoulder wheel with the eccentric spring.

The moment about at the centre, O , caused by the spring generates the mechanical impedance at the rotating wheel. Based on conventional mathematical and mechanical calculations, we can predict the mechanical impedance of the wheel.

All constant values such as r , d , and l are measured from the experimental setup. Spring stiffness, K is obtained by adding mass, measuring displacement of the spring and then using least square fitting. The stiffness was found to be 155.50 N/m.

Moreover, based on transduction matrix theory, mechanical impedance was measured in an experiment where the spring is attached to the shoulder wheel. In Figure 6, the theoretical data and the experimental data can be compared. We can see that they have a very obvious similarity.

As it is observable in Figure 6, there is a good agreement between the measured value and the analytical solution. This supports and validates the accuracy of the measurement method. Now the method is prepared to use for direct measurement of the human arm's mechanical impedance.

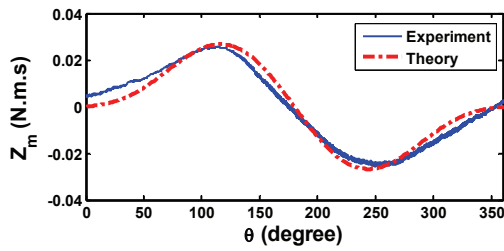


Figure 6: Experimental result (solid blue) of the mechanical impedance of a spring as compared to the theoretical solution (dashed red).

3.3 Arm's Impedance

While performing the one-dimensional rotary task with constant speed, the subjects change their arm's mechanical impedance on the wheel to synchronize their arm's movement with the rotation. Figure 7 to Figure 10 show the measurement results of the same experiment on two right-handed healthy subjects, a man and a woman both of which do the task with their right hand.

For both subjects, we observed the adaptation process in form of changes in mean cycle of the mechanical impedance, as well as ΔT and $\Delta\omega$. Where $\Delta\omega$ is the value of ω minus ω_0 which is the angular velocity measured at unloaded condition.

Figure 7 shows arm mechanical impedance of the two subjects where each performed the task 31 times. Curves in solid line are those of subject 1 while measurements on subject 2 are shown in dashed lines. We can see that density of the data is more near the axis $Z_m=0$. This can be explained by the nature of the task that the subject is asked to follow the motion without resistance or assistance which means the velocity of the subject's hand should be equal to that of the wheel. Should any discrepancy occurs, it is considered an error that is represented in terms of excessive mechanical impedance.

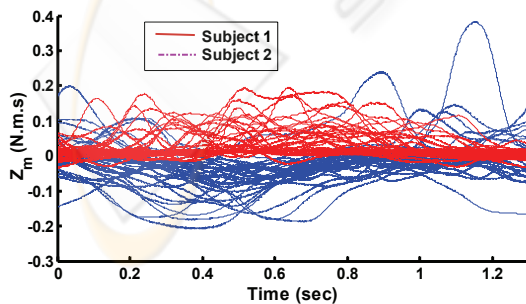


Figure 7: Arm mechanical impedance of two subjects; each subject performed the trial 31 times. Curves in solid line are those of subject 1 while measurements on subject 2 are shown in dashed lines.

In order to have a better understanding of how mechanical impedance changes during adaptation, mean value of the impedance curves are shown in Figure 8; in the graphs the error-bar represents the standard deviation of the impedance in each cycle.

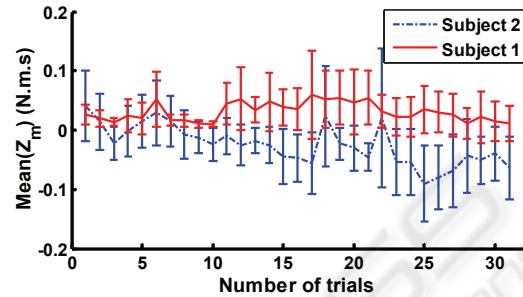


Figure 8: Mean value of arm mechanical impedance of two subjects doing 31 trials. Curves in solid line are those of subject 1 while measurements on subject 2 are shown in dashed lines.

Please note that the relatively high standard deviation is mainly because of the stochastic temperament of the biomechanical system.

Mechanical impedance is a product of T divided by ω thus an intrinsic property of a mechanical system. However in this biomechanical system, this property changes with neural signals. For example, when the neural signal is low density, the muscles are less stiff hence we expect that the impedance is lower comparing to a posture with high density neural signals. The value of ΔT measured in our experiment is proportional to the interaction force between the subject's hand and the wheel's handle. The interaction force, in turn, has to do with each single muscle's force. So if we study the changes of the measured mechanical impedance, we will have some clue about how neural signals of the muscles regulated to control the motion of the arm.

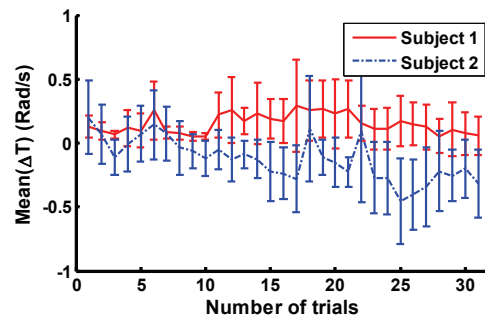


Figure 9: Mean value of the interaction torque of two subjects in 31 trials. Curves in solid line are those of subject 1 while measurements on subject 2 are shown in dashed lines.

Mean value and standard deviation of the torque, ΔT , is shown in form of an error-bar graph in Figure 9. In Figure 10 also, we can see the error-bar graph of mean value and standard deviation of $\Delta\omega$.

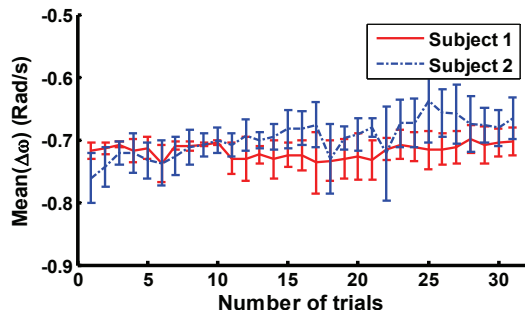


Figure 10: Mean value of hand velocity of two subjects in 31 trials. Curves in solid line are those of subject 1 while measurements on subject 2 are shown in dashed lines.

4 AN IMPEDANCE BASED INDICATOR

In this paper we used an electromechanical simultaneous sensor cum actuator to propose a method and a device which is capable of the measuring impedance, the torque, and the velocity during motion. In comparison with existing methods, this methodology is much simpler to use. More importantly, we can measure the impedance, the torque, and the angular velocity during any motion profile accurately. In conventional methods of impedance measurement, one needs to apply perturbation while our method does not require perturbation in a sense of an externally applied force. In our experiments, we applied a constant speed to the subject's limb while their actual reaching speed profile is always a bell-shape function. Then we measured impedance based on the resulted interaction force and the changes in the initial speed.

The experimental results showed that during adaptation to a rotational motion with constant speed, subjects adapted their arm's mechanical impedance with changing their interaction force and velocity.

The tests will be soon available to some stroke patients before, during, and after upper limb rehabilitation. The values of impedance, torque, and velocity will be analyzed and compared to Fugle-Mayer motor function assessment test in order to give the evaluators a quantifying tool to help them with an objective assessment.

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