Mechanical Impedance Modeling of Human Arm: A survey

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Abstract. Human arm mechanical impedance plays a vital role in describing motion ability of the upper limb. One of the impedance parameters is stiffness which is defined as the ratio of an applied force to the measured deformation of the muscle. The arm mechanical impedance modeling is useful in order to develop a better controller for system that interacts with human as such an automated robot-assisted platform for automated rehabilitation training. The aim of the survey is to summarize the existing mechanical impedance models of human upper limb so to justify the need to have an improved version of the arm model in order to facilitate the development of better controller of such systems with ever increase in complexity. In particular, the paper will address the following issue: Human motor control and motor learning, constant and variable impedance models, methods for measuring mechanical impedance and mechanical impedance modeling techniques.

1. Introduction

Motor control is important for effective human movement. Human motor control is the process by which human use their brain and cognition ability to activate and coordinate the muscles and limbs involved in improving the performance of a dedicated motor skill [1]. Most activities that are performed with the hands involve interaction with the environment. This interaction imposes forces on the hand and can also destabilize motion. However, human have excellent capabilities to manipulate objects. This means that the central nervous system (CNS) is able to adapt to various task dynamics. For instance, one may have difficulty in opening a door for the first time due to unknown friction. However, after many trials the appropriate force to be exerted will be learned, and one will open the door without difficulty and even without thinking about it. This situation may be regarded as impedance control [2] which can been described as an effective strategy of the nervous system to deal with kinematic variability such as due to neuromuscular noise and environmental perturbations.
In early works, impedance was assumed to be constant which allows the use of linear models [3]. In constant impedance model, they ignored environmental perturbations whereas in active impedance the perturbations and other noise elements are included.

Lance [4] was among the earliest who defined spasticity as a motor disorder characterized by a velocity dependent increase in tonic stretch reflexes (muscle tone) with exaggerated tendon jerks, resulting from hyper excitability of the stretch reflex, as one component of the upper motor neuron syndrome. High value in spasticity’s assessment reflects higher restriction in the functional range and speed of motion of the limb. Spasticity assessment has close relation to the mechanical impedance of the upper limb. Hogan et.al [1] reported that muscle co-activation invokes mechanical impedance of the limb and it is significant to perform tasks during specific therapy session. In addition, Burdet et.al [5] found that human learns how to stabilize the unstable movement by varying the mechanical impedance of the affected muscles.

Generally, mechanical impedance consist of a set of mass, spring and damper. These elements are important to measure the ability of the muscle in performing specific task [6]. The parameters are also used to describe the dynamic motion of a person. Mechanical impedance which is defined as the ratio of the force applied at a point to the resulting velocity at that point is strongly related to muscle activation [7]. Mass, spring and damper elements in mechanical impedance have been represented as inertia, stiffness and damping of the limb respectively. Therefore, mechanical impedance modeling is useful as it has direct relation with the level of assessment made on the muscle quality. However there is less discussion on the variability in the parameter of the mechanical impedance. In this paper, a review on human motor control and motor learning, measuring of mechanical impedance and different mechanical impedance modeling techniques is reported.

2. Literature Review

The paper is composed of four sections where in section 2.1 motor control and learning function for human will be elaborated. The subsequent section explains on the different between constant and variable impedance. Then, the method of measuring mechanical impedance was discussed in section 2.3. Section 2.4 summarizes the findings from other works that use different modeling to represent mechanical impedance of human arm.

2.1. Human motor control and Motor Learning

In order to develop model of human limb mechanical impedance, the understanding of human motor control in motor learning process is required. Human have the ability to quickly adapt to the movement changes according to internal and external disturbances. Therefore, when the human arm movement is interrupted, the arm tends to automatically return to the desired trajectory [8]. From that, human learns to control the muscle. Central Nervous Systems (CNS) determines the right muscles to be activated with correct amount of force and timing in order to track the desired trajectory. Furthermore, movement needs feedforward mechanism to strategize the force for the task to be done successfully. Shadmehr et.al [9] explained how the feedforward mechanism took place during task performance. The results showed that the feedforward control managed to reduce the movement error-trial and compensate the disturbances.

2.2. Constant and Variable Impedance

Each parameter of mechanical impedance is important to measure the ability of the muscle in performing a specific task. The value of the parameters varies at every instant in the trajectory and also affected by the variation in environment. In early works, impedance parameter was assumed to be constant and linear.

Hondori et.al [10] described mechanical impedance in terms of spring, mass and damper. Definition of impedance has been refer to average stiffness, defined as ratio between generalized force (force or torque) to generalized displacement (linear or angular) for the system [1]. The system that we focus is upper limb
as it is important for human daily activities such as grasp, flexion and extension. Mass, spring damper is represented of inertia, stiffness and viscosity respectively, whereby participate in order to perform the specific task smoothly and effectively.

In a view by Nikooyan et.al [11] muscle can be represented as a spring-damper lumped system, and it can be divided into two type of system models namely passive and active models. In passive model, the spring and damper was treated as constant parameters with additional nonlinearities term. In early modeling, constant impedance introduced whereby elbow to wrist joints represented by two-DOF. The work explained the dynamic response to vibration input to the arm and acknowledge that the arm system may be used as a low-pass mechanical filter that attenuates high frequencies. While Holmlund revealed that human impedance varies with direction, gender, level and posture by experiment done in measuring mechanical impedance during different condition and factor. Kistemaker et.al [14] claimed that when using constant coefficient for stiffness and damping factor, it leads to large error in the estimated parameter. They suggested that parameter estimation should use the moving-time-window algorithm. The use of time-window method provides mean to determine the time-dependent changes in joint stiffness and damping in human upper limb based on the data of the movement. It is crucial to model the upper limb using variable impedance parameter for stiffness and damping factor so as they can be adaptable in the application that requires interaction between human and systems. The model falls under the second model type that is active model.

2.3. Measuring Mechanical Impedance

In more recent rehabilitation robotic systems mechanical impedance plays vital role in making the system more human like [15]. It poses a challenge to measure the mechanical impedance of the limb thus researchers came out with different measuring devices with different techniques to measure the parameters.

Hondori et.al [16] proposed an experiment to measure dynamic mechanical impedance. He proved that human mechanical impedance varied when the limb moved. However the relation between the change in mechanical impedance and the learning process was not established. The system allowed the measurement of real and imaginary parts of mechanical impedance parameter separately where the real part was identified as mechanical resistance, which was also independent of frequency and the imaginary part was identified as mechanical reactance which varied with frequency. In his paper, he reported that postures affects mechanical impedance during reaching motion. In general the force and velocity are needed to measure mechanical impedance. Hence, the measurement system were developed to be able to measure and record the given force and velocity [17].

In the manual ways of conducting upper limb rehabilitation training for stroke patient, the therapist measures the muscle stiffness subjectively. The Modified Ashworth Scale (MAS) is the common assessment tool used by the therapist to measure the affected muscle quality or muscle tone of stroke patient. The scale is widely used to grade muscle spasticity. The grade is based on the relationship between the range of motion and resistance force during extension/flexion in the joint. According to Bohannon & Smith, there is high interrater reliability when using the MAS to assess the spasticity. Thus, introducing a quantitative measurement based on the MAS may help to overcome the lack of the traditional method. Uchiyama [18] had done the quantitative evaluation of spasticity in upper limb using mathematical model. He assumed that elastic coefficients were proportional to elbow angle and muscle activities. The elbow joint angle, torque, and electromyograms (EMGs) of the biceps brachii, triceps brachii, and brachioradialis muscles were measured. Furthermore, the limitation of this research only take account for elasticity response without depend on viscosity.

Characterization of average elasticity based on MAS assessment were established here. Likewise, Nima [19] conducted experiment using correlation method (Pearson’s correlation test) to analyse
relationship for both elasticity and viscosity with the MAS. Meanwhile, Ayuni [20] developed spasticity mathematical model based on the MAS +1 scored. Hence it shows strong positive linear correlation coefficient. The elbow joint system was developed as a one degree of freedom system to represent part-task trainer. Table 1 summarized the measuring method of mechanical impedance and spasticity.

Table 1: Measuring method of mechanical impedance and spasticity

| Author           | Measuring method                                      | Remarks                                                                                                                                                                                                 |
|------------------|-------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Noor Ayuni, 2015 | Spasticity of grade 1+ on MAS based mathematical model | Muscle tone is proportional to the velocity of the motion. The data collected focus only for motion with grade of 1+ in MAS. There is no muscle model used to measure the mechanical impedance and it involve two dynamics equations to represent the following case; 1) Muscle tone catch during slow and fast motion stretching 2) Resistance through range of motion |
| Nima, 2011       | Quantitatively evaluation of spasticity during passive flexion and passive extension | Analyzed relationship between viscous, elastic and MAS using correlation method (Pearson’s correlation test) and torque and position was the output.                                                        |
| Hondori, 2011    | Smart mug to measure geometrical impedance            | Vibration is applied to make perturbation in any direction. The result is impedance highly depend on wrist’s posture and hypothesis is bigger diameter gives most stable condition and vice versa. Input is centrifugal force and output is velocity |
| Hondori, 2010    | On Line learning process                              | Mechanical impedance changes with expertise (learning function). Experiment done by using electrical motor (electrical impedance) as sensor instead of force sensor and transduction matrix method. Force (torque) is the input and velocity (angular velocity) is the output. |
| Uchiyama, 2005   | Quantitatively evaluation of spasticity during passive flexion and passive extension | Characterize average elasticity based on MAS assessment based on muscle model without damper while include EMG signal. The inputs are elbow joint angle, torque and EMG (biceps brachii, triceps brachii and brachioradialis). Least square method(experimental) and Range-kutta method (estimation) used. |

2.4. Mechanical Impedance Modeling

Biologically, muscle comes with two sections which are thick (myosin) filaments and thin (actin). This part shown in figure 1. Myosin filaments slide against actin which tend to shorten the activated muscle. Neural activation signals is receive when muscle is activated. That signal consist of several spikes. The amount of force produce is depends on the frequency and magnitude of spikes.
In addition, muscle tension is count on both length and velocity. Experiment did by Burdet [21] to measure stiffness (K) and damping (B) for a cat’s muscle. As a result, when the length is equal to half of the initial length, muscle cannot generate force and same goes with the velocity. However, the force increases as length or velocity increases. Hence, the impedance of a single muscle changes with the force it generates.

**Figure 1:** Myosin and actin filaments in a muscle; figure adopted from http://sites.duke.edu

From the aspect of biomechanics systems, previous study has been introduces two type muscle models which are Maxwell model and Voight model. As it can be seen from figure 2 Maxwell model consists of a spring in series with a damper while Voight model has the spring in parallel with a damper. From a prospective of the input it shows that force step input and displacement step input tests from Voight’s model is more realistic than Maxwell model [22]. Even though the Voight’s model is more realistic, the limitation of these two model is none of them are capable of modeling the active contractile property of a muscle. After that many researchers come out with new modeling based on Voight model in order to predict the mechanical impedance of human’s upper limb.
Mechanical impedance model was illustrated by one or more mechanical elements into one system as described its function. Each element represents the function of the real systems. Mechanical impedance modeling is an important stage in order to determine quantitative assessment of the system which in this case is human arm. In this section, different modalities will be elaborated. It can be represents in two ways which are structure model and mathematical model. Previous studies had greatly used the mass-spring-damper systems (MSD) in representing mechanical impedance of human arm [23]-[25]. Equation 1 corresponds to the mass-spring-damper model shown in Figure 3. This is second order dynamic equation where $m_e(t)$, $b_e(t)$, and $k_e(t)$ are the impedance parameters which denote the mass, damping factor, and stiffness of the arm, respectively; and $f_e(t)$ representing the force exerted to arm.

Researchers have been done a quite number of experiments on mechanical impedance of human arm. Several disparate mathematical models are proposed for the representation of human arm movement. Recent years, MSD model has been improved to investigate mechanical impedance during movement of the arm [23]. They have included muscle activation as dependent parameter [26]. However this model was developed assuming that the system has simple joints and does not consider complex muscle mechanics and geometry because when dealing with muscle it is not easy as the shape is very irregular. As reported by Speich et al. [24] and Rahman et al. [27] was developed a model with five parameters with additional spring and damper to better approximate the dynamics systems. Then, Shuaijie et al. [28] was studied the mechanical impedance during maintained posture and reaching movements in order to analyzed human impedance changes depending on the situation. The similar study by Tasnuava et al. [29] introduced Rayleigh’s dissipation factor for the damping action, Lagrangian approach is applied to develop the mathematical model of human arm during movement.

David et al. [30] distinguish two models which are viscoelastic model and Hill’s model. Viscoelastic model only consider spring and damper while Hill’s model consist of three elements which are contractile element (CE), and constant value of spring. These models preferred use when it interacts with
musculoskeletal systems and mass neglected. Table 2 summarizes different modeling of human arm mechanical impedance.

\[
m_e(t)\ddot{x}(t) + b_e(t)\dot{x}(t) + k_e(t)x(t) = f_e(t)
\]

(1)

**Figure 3:** Mass-spring-damper model for human arm’s mechanical impedance

**Table 2:** Different modeling of human arm’s mechanical impedance

| Author   | Model of Human Arm                                                                 | Remarks                                                                 |
|----------|-----------------------------------------------------------------------------------|------------------------------------------------------------------------|
| David    | Based on human neuromuscular system impedance.                                    | Using Hill muscle model and viscoelastic model acts as machine.        |
| 2013     |                                                                                   | Experimentally for subjects to differentiate between 'machine' and 'human'. |
| Choudry  | Lagrangian based model during dynamics planner motion                               | Lagrangian method reduces the mathematical complexity and consider active movement only. |
| 2013     |                                                                                   |                                                                        |
| Wang     | Considered that hand inertia, viscosity and stiffness constant during disturbance because of low degree and short duration of the disturbance. | Noisy and unstable force uncontrolled.                                  |
| 2011     |                                                                                   |                                                                        |
| Artemiadis | End-point dynamic based on second order system in 3D space.                      | A comparison of the five parameter model with a two parameter spring-damper model suggests that in some cases the use of additional model may not significant improvement. |
| 2010     |                                                                                   |                                                                        |
| Speich   | Five parameters model by additional spring and damper.                           |                                                                        |
| 2005     |                                                                                   |                                                                        |
Spring and damper systems representation of biceps and triceps muscle. Mass refers to the arm. A second order equation was considered as the model for arm dynamics. For calculations, ARX (Auto Regressive eXogenous) model presented and minimum jerks applied.

3. Conclusion
In this paper, different structure and mathematical models of mechanical impedance in modeling human arm is discussed. In particular, the impedance values have direct relation to human motor control and motor learning. It can also be represented as constant or dynamics parameters where the value varies upon changes in force and velocity as well as posture and the environment.

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