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Smart Mug to Measure Hand's Geometrical Mechanical Impedance

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Abstract—**A novel device, which looks like a mug, has been proposed for measuring the impedance of human hand. The device is designed to have convenient size and light weight similar to an ordinary coffee mug. It contains a 2-axis inertia sensor to monitor vibration and a small motor to carry an eccentric mass (m=100gr, r=2cm, rpm=600). The centrifugal force due to the rotating mass applies a dynamic force to the hand that holds the mug. Correlation of the acceleration signals with the perturbing force gives the geometrical mechanical impedance. Experimental results on a healthy subject shows that impedance is posture dependant while it changes with the direction of the applied perturbing force. For nine postures the geometrical impedance is obtained all of which have elliptical shapes. The method can be used for assessment of spasticity and monitoring stability in patients with stroke or similar problems.**

I. INTRODUCTION

Assessment of human motor function has been difficult because of the complexity of human brain and the subjective nature of the assessment. Widely-known scoring methods such as Fugel-Mayer [1] for rehabilitation assessment are generally subjective and qualitative; thus there have been attempts to replace them with automated tools or to enhance them by integrating them with quantitative scales. Robotic researchers too have tried to introduce their machines to measuring the subject's performance for the assessment [2]. Most of the robots that have been used so far are rather complicated and expensive hence they are found in only small number of rehab centers. This paper presents an easier yet reliable tool for the assessment of motor function. Regarding the quantity that new tool measures and its simplicity of use, the overall performance can be better than a robot.

To monitor and assess the motor performance it is important to select a measure that represents, accurately and reliably, the quality of the task being performed. Usually, the measures are kinematic, kinetic, and temporal variables. Kinematic variables include displacement, velocity, and higher-order derivatives such as acceleration. Kinetic variables are related to force and torque while temporal variables take in timing of a sequence of movements, total duration to complete movement, total time on target during a tracking task, etc [3]. To choose the best measure we should consider the mechanism of motion execution.

The simplest tasks are single joint movements and human performs these tasks with bi- or tri-phasic patterns of muscle activity [4]-[5]. The commands are in form of feed-forward electric signals and they are sent down to the agonist (the muscle that produces the positive torque in the joint) and antagonist muscles (the muscle corresponds with the negative torque) [6].

To perform a single joint task, firstly the agonist muscle is fired to accelerate the limb toward the target. The size of this burst of activity will increase if the subject wants to increase the speed or length of the movement [4]. Then, with the limb getting close to the target, the second burst of activity decelerates the limb is by the antagonist activation [7]. Finally when the limb reaches the target it will be time for the third burst to activate and keep activating the agonist muscle to maintain the limb's posture at the target position [8]. The three phases can be adjusted so that the task is done with the required amplitude, duration, and velocity [7].

The bursts of muscle activities change with learning. At the beginning there is a considerable amount of antagonist activation which is inconsistent. However with practice, the variability decreases dramatically and concurrently there appears a gradual falling trend in the antagonist muscle activities [9].

Hogan [10] and Hondori et al [11] showed that the antagonist muscle's co-activation is to generate mechanical impedance which is necessary to perform some tasks. A typical case with the necessity is performing a dynamically unstable task. Burdet et al [12] showed that human learns and controls unstable dynamics by optimizing mechanical impedance. Darainy et al [13] reported that the EMG patterns of dynamic learning reveals a considerable portion of co-activation in mechanically stable tasks. Moreover, when the main signal of muscle's electrical activation increases, the muscle's noise will raise as well. The noise is known as signal dependent noise and it determines motor planning [14]. However impedance control, again, is the strategy to reduce instability that arises from the noise [15].

The co-contraction of the antagonist muscles that sets the impedance of the limb is observed in both stable and unstable tasks. Therefore learning would literally mean acquiring the efficient co-activation or controlling the mechanical impedance of the limb.

Regarding the importance of mechanical impedance and incapability of the conventional methods to measure it in form of a complex number, this research aims to propose a novel method for measuring human hand's mechanical impedance (in the wrist joint) which is usable for the

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assessment of motor function of patients undergoing rehabilitation.

II. METHODOLOGY

A. What is mechanical impedance

Mechanical impedance represents mass, stiffness and damping combined. It is the ratio of a phasor representing a sinusoidally varying force applied to a system to a phasor representing the velocity of a point in the system. The real part of the impedance, the mechanical resistance, is independent of frequency; the imaginary part, the mechanical reactance, varies with frequency, becoming zero at the resonance. For a mechanical system impedance, z_m, at frequency equal to ω can relate force, F, to velocity, v, according to equation (1).

$$F(\omega) = z_m(\omega) \times v(\omega) \qquad (1)$$

B. How to Measure Mechanical Impedance

To measure mechanical impedance, one needs to measure the force and the velocity and calculate the ratio of them. A human limb's impedance is usually measured using a robot that applies a perturbation to the hand and records the force and the velocity [2], [12], [16]-[17].

We need a sinusoidal force perturbation at the output side of transduction matrix [18] or [19]. Then the resultant velocity of the load has to be recorded. If we apply a sinusoidal force, the velocity is almost a sinusoidal with the same frequency but it carries a phase shift.

Assuming there is a 1DoF mass-spring-damper mechanical system to which force, F, is applied as a perturbation and velocity, v, is the response to the perturbation.

Since v sometimes becomes equal to zero, that makes impedance approach toward the infinity, first we have to obtain the analytical signals, $\widetilde{F}$ and $\widetilde{v}$ using Hilbert transform; equation (4). Then we introduce them to equation (5). The mechanical impedance is obtained by dividing force by velocity; equation (5). The mechanical impedance obtained from equation (5) is a complex number and its absolute value is equal to 0.0125.

Mechanical impedance of human hand cannot be explained by a one-DoF mass-spring-damper system so its impedance is not a single number. Instead the impedance changes according to the direction of perturbation applied. We must calculate the impedance in any direction (i.e. angle) by dividing the magnitude of the force perturbation over the magnitude of the velocity response. Finally a polar graph will represent the impedance value vs the angle at which it was measured.

$$\begin{aligned} \widetilde{v} &= v + j(Hilbert(v)) \\ \widetilde{F} &= F + j(Hilbert(\dot{F})) \end{aligned} \qquad (4)$$

$$z_m = \frac{\widetilde{F}}{\widetilde{v}} \qquad (5)$$

III. DESIGN OF THE DEVICE

The idea is to design a mug-like vibrator equipped with an inertia sensor, Figure 1. The design should be very convenient because the device has to have the shape and weight of an ordinary mug. It is effective because it accurately measures the response to perturbation in any direction.

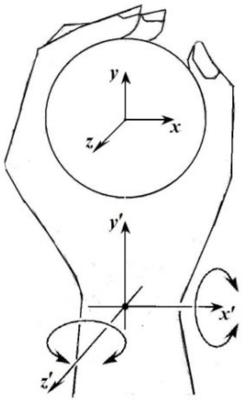

Figure 1: schematic picture of the mug held by the subject's hand. The origin of x-y-z coordinates lies on the coordinates of the inertia sensor. The wrist rotates around x' and z' axes

The device in Figure 2 was customized for measuring the wrist impedance. The working principle of the device, as shown in Figure 3, is that the rotation of the eccentric mass (rotated by the DC motor inside the mug) causes a centrifugal force. We know the amount of force based on the motor speed and the mass and eccentric radius. The force will cause vibration along x and y axes. In any moment in time we continuously measure vibration acceleration along x and y using the sensor and use the data to obtain the impedance.

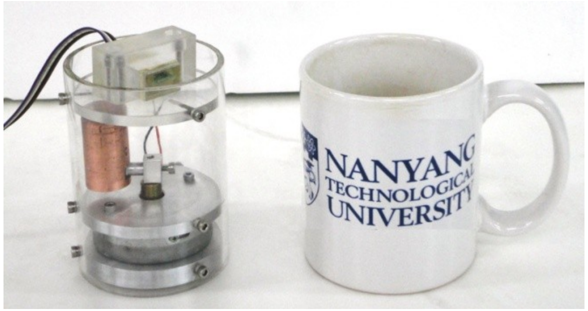

Figure 2: the device after fabrication compared to a normal coffee mug

IV. SIMULATION OF MECHANICAL IMPEDANCE

Figure 3 shows the schematic picture of the device while the impedance of the hand in x-y plan is replaced by two sets of mass-spring-damper systems.

Equation (7) is the state space equation of system of Figure 2b which is derived from equation (6).

In all simulated systems, damping along x or y is equal to 0.2 time the stiffness of the same axis. So looking at Table 1 all values of the mass-spring-damper along x and y can be identified. Introducing the values to the MATLAB code, written to simulate the velocity and displacement, we were able to find velocity of the vibration along x and y. We used MATLAB to solve the state space equation (7) and then introduced the solution to equation (5) and equation (4) respectively. The outcome is the mechanical impedance which is shown in Figure 4.

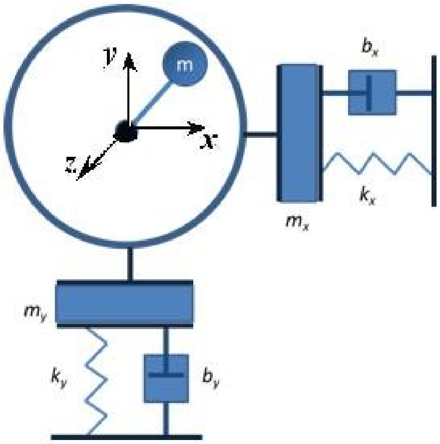

Figure 3: two-DoF mass spring damper to simulate hand's impedance

Table 1: stiffness and mass values of the simulated systems

	k_x	k_y	m_x	m_y
A	400	400	0.1	0.1
B	300	600	0.1	0.05
C	600	300	0.05	0.1
D	200	600	0.5	0.1

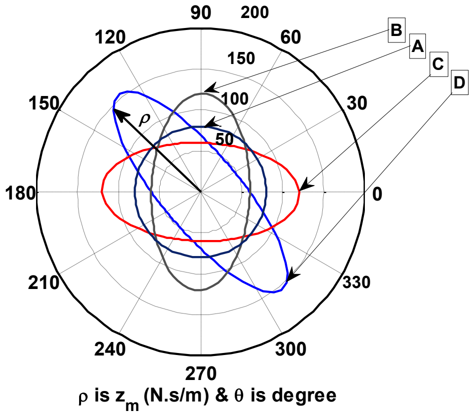

Figure 5: polar representation of geometrical mechanical impedance of the simulated systems; four ellipses attribute to four systems in Table 1. The ρ in the polar diagram is equal to force divided by velocity in the direction θ

$$\ddot{x} = -\frac{k_x}{m_x}x - \frac{b_x}{m_x}\dot{x} + \frac{1}{m_x}F_x$$
$$\ddot{y} = -\frac{k_y}{m_y}y - \frac{b_y}{m_y}\dot{y} + \frac{1}{m_y}F_y \qquad (6)$$

$$\begin{Bmatrix}\dot{x}\\ \ddot{x}\\ \dot{y}\\ \ddot{y}\end{Bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0\\ -\frac{k_x}{m_x} & -\frac{b_x}{m_x} & 0 & 0\\ 0 & 0 & 0 & 1\\ 0 & 0 & -\frac{k_y}{m_y} & -\frac{b_y}{m_y}\end{bmatrix}\begin{Bmatrix}x\\ \dot{x}\\ y\\ \dot{y}\end{Bmatrix} + \begin{bmatrix} 0 & 0\\ \frac{1}{m_x} & 0\\ 0 & 0\\ 0 & \frac{1}{m_y}\end{bmatrix}\begin{Bmatrix}F_x\\ F_y\end{Bmatrix} \qquad (7)$$

V. EXPERIMENTAL PROCEDURE AND RESULTS

The subject holds the mug with his left hand, according to Figure 5. The experiment is repeated in 9 different postures as shown in Figure 6; the diagram shows two axes namely: flexion/extension (around z' axis) and abduction/adduction (around x' axis).

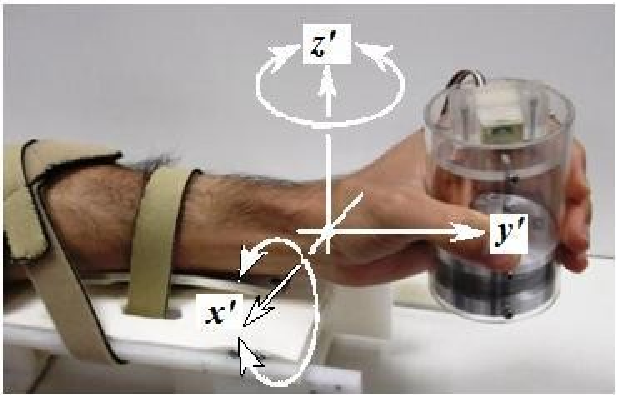

Figure 5: the subject holding the mug; the wrist joint rotates around x' and z' axes to position in 9 points shown in Figure 6

In each point while the subject maintains the posture, the mug applies perturbation to the hand and the vibration response is recorded via the inertia sensor. As explained in earlier section, the mechanical impedance is obtained using equation (8) to (11).

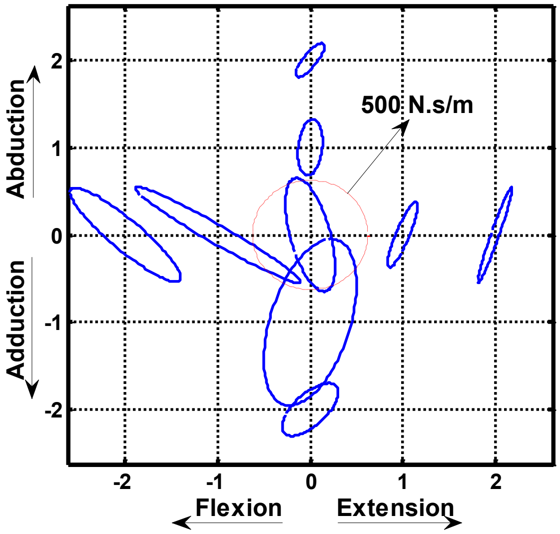

Figure 6: geometrical mechanical impedance and the left hand

VI. Discussion

Figure 6 shows the mechanical impedance of human hand; it can be observed that the impedance is highly dependent upon wrist's posture. More over in any posture the impedance is not a single value but is a function of the direction of the perturbation. That means depending on which direction the force is applied impedance can be different. In Figure 6 for each posture impedance diagram is found to be an ellipse. The bigger diameter shows the direction in which hand is most stable while the smaller diameter attributes to the least stable direction. It has been found that mechanical impedance of human arm is optimized to cope with destabilizing dynamics; for the future work we are interested to check our system to see how these impedance ellipses are tuned when the hand is subject to unstable dynamics.

VII. Conclusion

In this research we examined the novel smart mug's design that applies the centrifugal force of a rotating eccentric mass to the hand of the person who holds it and records the acceleration response. The force is continually decomposed into its x and y components and the vibration responses to each are recorded using an inertia sensor. The acceleration signal is integrated to give the velocity signal which is used for calculating mechanical impedance.

The experimental results for 9 postures in a healthy human subject showed that the impedance diagram is an ellipse for any posture; that indicates the dependence of mechanical impedance on the direction in which we measure it. Largest and smallest impedance are attributed to the major and minor diameters of the impedance ellipse. The direction of the minor and major diameter also show the direction in which the hand is least and most stable respectively. Over all, the design and method worked successfully.

VIII. Acknowledgment

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