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A portable system for quantitative assessment of parkinsonian rigidity

Houde Dai, Bernward Otten, Jan Hinnerk Mehrkens, L. T. D'Angelo, *Member, IEEE*

Abstract— **Rigidity is one of the primary symptoms of Parkinson's disease. Passive flexion and extension of the elbow is used to assess rigidity in this study. An examiner flexes and extends the subject's elbow joint through a rigidity assessment cuff attached around the wrist. Each assessment lasts for 10 seconds. Two force sensor boxes and an inertial measurement unit are used to measure the applied force and the state of the elbow movement. Elastic and viscous values will be obtained through a least squares estimation with all the data. 9 healthy subjects were tested with this system in two experimental conditions: 1) normal state (relaxed); 2) imitated rigidity state. Also the subjects were performed the assessment task with different frequencies and elbow movement ranges. The imitated rigidity action increases viscosity and elasticity. The effect sizes (Cohen's *d*) of the viscosity and elasticity between normal state and imitated state are 1.61 and 1.36 respectively, which means the difference is significant. Thus, this system can detect the on-off fluctuations of parkinsonian rigidity. Both wrist movement angle and frequency have small effect on the viscosity, but have elevated effect on the elasticity.**

I. INTRODUCTION

Tremor (rhythmic back and forth motion), bradykinesia (slowness of motion) and rigidity (resistance to movement) are the three primary symptoms of Parkinson's disease (PD). Tremor is the most apparent and well-known symptom of PD [1]. However, rigidity responded immediately upon PD Treatment [2]. It refers to a permanently elevated muscle contraction, independent of passive movement velocity. Patients with severe rigidity can hardly reach muscle relaxation and their voluntary movements are accompanied by an elevated contraction of antagonist muscles [17].

In clinical practice, rigidity assessment is realized through passive movement of the subject's limb, which is controlled by a neurologist or other examiner. The level of instinctive resistance to the exerted movement is scored according to the Unified Parkinson's Disease Rating Scale (UPDRS). Based on experiences, the examiner classifies rigidity on a scale from 0 to 4, which compared to a control group [4].

The UPDRS is a subjective rating and the rigidity scores for the same patient may differ widely depending on the examiner [5].

Rigidity occurring in PD commonly has a "cogwheel" character, which is not represented by the UPDRS [6].

This subjective assessment leads to problems when evaluating the effectiveness of therapies for PD.

II. STATE OF THE ART AND TASK DESCRIPTION

A. *State of the Art in Rigidity Assessment*

For the rigidity assessment in PD, there are no available devices on the market. But some researchers try to explore the relation between biomechanical parameters and the UPDRS rigidity scale [7-11]. For operation of most researches, an examiner or a motor drive flexes and extents a joint repeatedly, then parameters from the applied torque are calculated. However there are also researchers who calculate rigidity parameters from the electromyographic potentials during flexion and extension movement [8]. Reference [9] indicated that the correlation of mechanical properties with the UPDRS scores is superior to the correlation of electromyography (EMG) with the UPDRS scores (correlation coefficient: 0.60-0.86 compared to 0.37-0.79).

Quantification of the mechanical properties of a joint can be realized by passive joint movement, for example, flexion and extension of the joint by a clinician or a torque motor. Some approaches use kinematics to restrict the movement of the limbs, while others do not. Rigidity is commonly assessed in the upper limbs at the wrist and elbow. An overview of recent approaches is given in Table I.

TABLE I. SUMMARY OF THE STATE OF THE ART

Ref.	Joint	Motor actuation	Angle measurement	Parameters
[2]	Wrist	Yes	Capacitive transducer	Work
[9]	Elbow	No	Gyroscope	Mechanical impedance
[10]	Wrist	No	Potentiometer	Viscoelastic values
[12]	Elbow	No	Gyroscope	EMG, torque bias
[19]	Elbow	No	Length gauge	Viscoelastic values

According to reference [9], expense, complexity and time involved are the most common reasons for not introducing

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Houde Dai, Bernward Otten and Lorenzo T. D'Angelo are with the Institute of Micro Technology and Medical Device Technology (o. Prof. Dr. Tim C. Lueth), Technische Universität München, 85748 Garching, Munich, Germany, (corresponding author to provide phone: +49 8928915181, e-mail: gu53tiz@mytum.de).

Jan Hinnerk Mehrkens is with the department of Neurology of Klinikum Großhadern at Ludwig-Maximilian University, D-81377, München, Germany.

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quantitative rigidity evaluation in clinical praxis. Elastic stiffness depends on the torque and angular displacement.

If a joint shows viscous behavior, it means that the measured torque depends on movement velocity. In order to avoid modeling the viscous component, some research groups chose to maintain a constant velocity by using motor actuated systems or advising examiners to impose same movement on all subjects. This is a burden for the user in daily use. Hence this is the motivation to model the viscous property in this study [11].

A potentiometer is easy to use for angle estimation. But potentiometer requires the examiner to strap the patient's limbs to some kind of cinematic device. Using gyroscope or accelerometer as the single source for angle calculation also has disadvantages [12]. With the rapid development of MEMS (Micro-Electro-Mechanical Systems) inertial sensors, the combination IMU device (Inertial Measurement Unit), which means the sensor fusion implementation of a 3-axis accelerometer and a 3-axis gyroscope, is currently used for angular displacement measurement in rigidity assessment in PD.

B. Task Description

The goal of the present project is to develop a portable assessment system to quantify parkinsonian elbow rigidity. The rigidity assessment system consists of a rigid cuff, which can be attached to the wrist, and a graphical user interface (GUI) in a computer [13]. The rigidity assessment cuff is designed to get the model of joint movement state (angular displacement and velocity) and measured torque (N·m), which includes non-neural torque and neural torque. The viscosity and elasticity of elbow, which are the major components of mechanical impedance, are calculated with the sensor data and displayed in the GUI [14-16].

III. SYSTEM CONCEPT

A. Assessment Task

Fig. 1 shows the rigidity cuff and rigidity quantification task. The rigidity cuff is strapped to the distal end of the test subject's forearm. An examiner flexes and extends the elbow joint through force at the rigidity cuff on the wrist. Each assessment task lasts for 10 seconds.

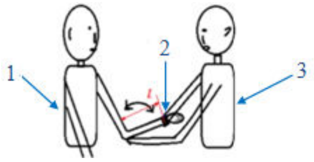


Figure 1. Assessment task. 1: subject; 2: rigidity cuff; 3: examiner. Here *l* is the arm length of the subject.

Because the movement of the wrist and elbow has two directions: passive (PA) and contralateral active (CA), both sides of the wrist need a force sensor.

B. Static System Concept Description

Fig. 2 shows the system diagram of the rigidity assessment system. The rigidity cuff is connected to the computer via a USB cable. The wired communication, instead of wireless communication, has the advantage that this system even can be used in the operation room.

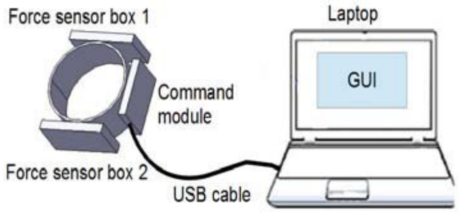


Figure 2. System diagram of the rigidity assessment system.

Each force sensor box includes four force sensitive resistors (FSR), which are in parallel connection to one output. Then it connects one end to the power supply and the other to a pull-down resistor to the ground. The point between the fixed pull-down resistor and the force sensor box is connected to the analog input of a microcontroller. Comparing to a single force sensor, the force sensor box has the benefits of higher measurement stability and bigger contact patch for the examiner. Two force sensor boxes are connected to the command module. Also the IMU part (a 3-axis gyroscope and a 3-axis accelerometer) is included in the command module. All the data are transmitted to the computer via serial-to-USB communication interface.

C. System Concept Description

At first, the IMU part was calibrated and verified. Because a force sensor box has 4 FSR sensors and the force-resistance characteristic is nonlinear, a 2-term Gaussian regression function was used for force sensor boxes calibration.

The 3-axis elbow angles (α) during rigidity task can be calculated from IMU outputs ($a, \dot{\alpha}$) in real-time using Direction Cosine Matrix fusion (DCM) algorithm [17].

The calculation of elastic stiffness (c) and viscosity (d) is realized by using a least squares parameter estimation method (regression analysis) to solve the following equation with 10 seconds data.

$$T = (F_1 - F_2) \cdot l = c \cdot |\alpha| + d \cdot |\dot{\alpha}| + e \tag{1}$$

where

T : torque measured;
$a, \dot{\alpha}$: acceleration and angular velocity;
F_1, F_2 : outputs of the force sensor boxes;
l : forearm length of the subject;
e : constant offset of the sensors.

Mechanical impedance is the feature for UPDRS rigidity score [9], and is calculated as follows:

$$Z = c + d \cdot \omega = c + d \cdot 2\pi \cdot f \tag{2}$$

where f is the frequency of elbow movement and calculated by a peak detection algorithm on the $\dot{\alpha}$ data; $d \cdot 2\pi \cdot f$ is the viscous stiffness.

In order to acquire the relation between mechanical impedance and UPDRS score, the relation of elastic stiffness and viscosity with the rigidity severity should be investigated firstly.

IV. SYSTEM PROTOTYPE AND EVALUATION

A. *Materials and Methods*

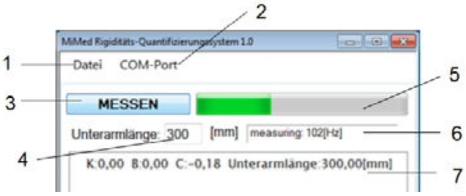
An accelerometer (MMA8452Q, Freescale Inc.) measures linear acceleration while a gyroscope (IMU3000, Invensense Inc.) measures angular velocity. Force sensor (FSR-149NS, IEE Inc.) has the measurement range from 0 to 100N.

All the sensor data are sampled at 100 Hz by the microprocessor (Atmega 328p).

Fig. 3 shows the first prototype of the rigidity cuff.

Figure 3. Overview of the prototype.

Data communication and the GUI were realized with Visual c# (Microsoft). This program invokes Matlab (MathWorks Inc.) to perform signal processing. Fig. 4 shows the GUI of the rigidity assessment system.



Unterarmlänge: 300 [mm] measuring: 102[Hz]

K:0,00 B:0,00 C:-0,18 Unterarmlänge:300,00[mm]

Figure 4. The GUI of the rigidity assessment system. 1: raw data path configuration; 2: serial interface setting; 3: start button; 4: input box for the patient's forearm length; 5: progress bar; 6: communication status; 7: results.

Because the forearm length cannot be measured directly with the above sensors, the examiner should input the subject's forearm length in the input box of the GUI.

B. *Experiment*

1) *Motivation*

In the presented experiment, the rigidity assessment algorithm is assessed.

2) *Setup*

9 healthy volunteers (average age: 24.4 ±4.2 years) were tested with the system, each for 8 times measurement. During first 4 times, the volunteers were asked to relax (with no rigidity and as the reference), while the other 4 times they were asked to perform with imitated rigidity. Also, during the assessments, the examiner tried to perform different elbow movement ranges and frequencies according to Table II.

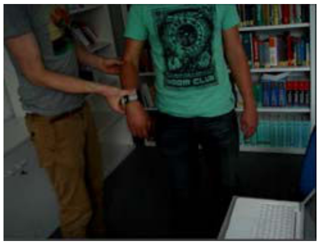


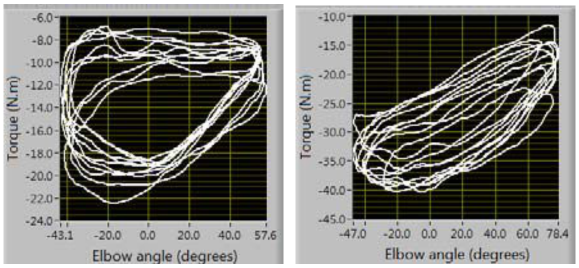
Figure 5. Experiment with the rigidity assessment system.

TABLE II. RIGIDITY ASSESSMENT TASKS

Nr.	**Range**	**Frequency**
1	60°	0.5 Hz
2	60°	1Hz
3	120°	0.5 Hz
4	120°	1Hz

3) *Results*

Fig. 6 shows the torque–displacement plots both in normal condition (relaxed state) and imitated rigidity condition.



a b

Figure 6. Torque–displacement plots. a: normal condition (relaxed), 100°, 1.2Hz; b: imitated rigidity condition, 120°, 1.1Hz.

The viscosity values, elasticity values and frequencies during the measurements were calculated with the algorithms stated above.

The result shows that the frequencies and ranges of movement were not exactly same to the settings in Table II, because it was very difficult for the examiner to keep accurate movement frequency and or range during assessment.

The viscosity and elasticity were converted to absolute values before calculation. The average value of viscous modulus with no rigidity (relax state) is 0.26 ± 0.08 N·m/degree, and 0.78 ± 0.45 N·m/degree is for the imitated rigidity state. The mean value of elastic modulus with no rigidity (relax state) is 0.99 ± 0.53 N·m/degree, and 3.78 ± 2.85 N·m/degree is for the imitated rigidity state.

The effect size (Cohen's *d*) of viscosity and elasticity between normal state and imitated state are 1.61 and 1.36, respectively. For Cohen's *d*, an effect size of 0.8 to infinity means a "large" effect [18].

The mean values and standard deviation values of viscous modulus and elastic modulus in different movement ranges and frequencies are displayed in Table III.

TABLE III. MEAN AND STANDARD DEVIATION OF THE ABSOLUTE VISCOSITY AND ELASTICITY

	Range		**Frequency**	
	≈ 60°	***≈ 120°***	***≈ 0.5 Hz***	***≈ 1Hz***
Viscosity (normal)	0.28±0.08	0.23±0.09	0.25±0.08	0.26±0.09
Viscosity (rigidity)	0.79±0.46	0.77±0.44	0.80±0.55	0.76±0.39
Elasticity (normal)	1.15±0.83	0.82±0.51	0.81±0.51	1.18±0.62
Elasticity (rigidity)	3.55±3.43	4.01±2.47	3.55±2.95	4.02±2.96

The result shows that the frequency and range of elbow movement have small effect on the viscosity. In contrast, movement frequency has greater effect on the elasticity, which might have negative influences when the examiner flexes and extends the forearm at different speeds. As a result, if the neurologist wants to obtain the mechanical impedance according to (2), it is important to keep the same frequency. Elasticity varies largely in the imitated rigidity state.

According to (2), the elasticity depends on the movement frequency and range and other factors. Thus, the mean value of elastic modulus has a big standard deviation. Another reason is that the tests performed imitated rigidity not in the same state, which means the imitated rigidity varied.

V. CONCLUSION

The first prototype of a portable rigidity assessment system based on force sensor boxes and IMU was presented. It is easy to perform with passive elbow movement. Because quantitative rigidity assessment in PD is difficult and depends on many factors, a comparison experiment was carried out. The result indicates that viscosity and elasticity in the imitate rigidity condition are bigger than normal condition (relaxed state). As a result, this system can detect the on-off fluctuations of parkinsonian rigidity [19].

The next steps consist in carrying out measurement with PD patients. With the measurement data, the correlation between mechanical impedance (viscosity, elasticity and movement frequency) and UPDRS scores can be determined. After that, the system can be used for rigidity assessment in PD.

Together with tremor and bradykinesia assessment system, a portable monitoring system used to quantify all primary neurological symptoms in PD can be realized.

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