

Active Motion Evaluation by Mechanical Power Factor Analysis Based on Specific Frequency Component

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This paper proposes a new approach of mechanical power factor analysis for evaluating human active motion. The mechanical power factor is affected by the motion trajectory of an evaluation object. Therefore, in active motion, unified evaluation is difficult using the conventional analysis method. In this study, the power factor evaluation of active motion is realized by applying the perturbation from the evaluation system and using its frequency component for power factor calculation.

Keywords: human support, power factor, motion evaluation, motion control, force control, compliance control

1. Introduction

Hemiplegic patients have difficulty with voluntary muscular contraction by spastic paralysis or sensation disorder. Aged people are liable to have paralysis by cerebral vascular disease, and that population is increasing. In clinical practice, a therapist rebuilds the body function of the patient by creating a rehabilitation training program. However, the diagnostics such as palpation or inspection depends on the experience of the therapist or doctor. In dealing with these issues, many evaluation methods for body function in quantitative way have been proposed in the field of engineering⁽¹⁾⁽²⁾. Along with the improvement in computer performance and measurement technology, the analyses of various biological data and motion data are realized. One of the biological signals used for evaluating body function is surface electromyogram (sEMG)^{(3)–(6)}. sEMG can measure the electrical activity which occurs in muscular contraction. In addition, motion capture system can record the position and movement which are features of human motion⁽⁷⁾. However, the measurement systems of these methods tend to be large because many sensors and electrodes are needed. On the other hand, many estimation methods for mechanical impedance of each part of body have been also proposed in this field^{(8)–(10)}. Human has a function of impedance adjusting to hold the stability of posture and motion. In the case of paralysis, failure of impedance adjustment occurs by abnormal muscle tone, and energy loss

may occur during motion. The authors already confirmed that energy loss during exercise can be evaluated using the concept of mechanical power factor^{(11)–(13)}. In past study, the power factor when applying external force from the system to the upper limb in relax state is evaluated. If this evaluation method can be applied to active motion, the evaluation of extension and bending operation would be realized. However, the unified evaluation is difficult because power factor depends on the trajectory of the motion. In addition, we have not considered the situation that external force which is applied by the system and human operating force are mixed.

In this study, the mechanical power factor analysis for human active motion is realized by applying perturbation from the evaluation system and using its frequency component for power factor calculation.

This paper is organized as follows. In section 2, the concept of mechanical power factor is shown. In section 3, power factor analysis focusing on the specific frequency component is proposed. In section 4, experimental verification of proposed method is shown. This paper is summarized in the last section.

2. Concept of Mechanical Power Factor

2.1 Power Factor in Electrical System This subsection explains the concept of power factor in electrical system. In electrical system, power factor is one of the indexes which represent the characteristics of energy transmission. Three kinds of electric power are defined in alternative current system; “active power”, “reactive power”, and “apparent power”. Active power means the electric power which is actually consumed at a load. On the other hand, reactive power is the electric power which is not consumed and return from load side to source side. Apparent power is the sum of active power and reactive power. Then, power factor is obtained from the ratio between active power and apparent power. We are able to know the value of voltage and current which is enough to perform the work by analyzing the power factor.

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Table 1. Analogies of variables

Electrical system	Mechanical system
Voltage v [V]	Force f [N]
Current i [A]	Velocity \dot{x} [m/s]
Power P [W]	Power P [W]
Inductance L [H]	Mass m [kg]
Resistance R [Ω]	Viscosity d [Ns/m]
Elastance (inverse of Capacitance) $1/C$ [1/F]	Stiffness k [N/m]

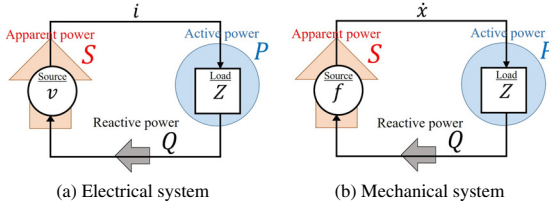


Fig. 1. Circuit representation of power factor

2.2 Power Factor in Mechanical System

Table 1 shows analogies of variables between electrical system and mechanical system. Based on the analogy between mechanical system and electrical system, power factor can be defined in mechanical system. The merit of using the mechanical power factor in this study is that the impedance characteristics of the body during motion can be obtained. The relationship of mechanical power factor is shown in Fig. 1. In this figure, Z signifies the load impedance. In mechanical system, velocity occurs when force acts to the load. This phenomenon is similar to the relationship between voltage and current in electrical system. Ideally, the system uses the maximum power to transfer energy to the load. However, like electrical system, it is rare that all the energy supplied from the source is consumed on the load side. The power which is not consumed at the load returns to the source. In order to apply the concept of power factor to mechanical system, the definition of three kinds of power are necessary. The maximum power that the source can be supplied is called “apparent power: S ”. In addition, “active power: P ” is defined as the power that is consumed by the load. By contrast, “reactive power: Q ” means the power that is not consumed by load.

From the relationship of analogy, active power can be defined as the time average of instantaneous power.

$$P = \frac{1}{T} \int_0^T f \dot{x} dt \dots \dots \dots (1)$$

In this equation, f and \dot{x} means the instantaneous force and velocity. T is period. Active power includes the magnitude and phase signal. On the other hand, apparent power is derived from root mean square (RMS) value of force: F_{rms} and velocity: \dot{X}_{rms} .

$$F_{rms} = \sqrt{\frac{1}{T} \int_0^T f^2 dt} \dots \dots \dots (2)$$

$$\dot{X}_{rms} = \sqrt{\frac{1}{T} \int_0^T \dot{x}^2 dt} \dots \dots \dots (3)$$

$$S = F_{rms} \dot{X}_{rms} \dots \dots \dots (4)$$

Apparent power only focuses on the magnitude of signal unlike active power. Power factor in mechanical system

(MPF) is derived as (5). This explains the how much of the supplied power is really used in the work.

$$MPF = \frac{P}{S} = \cos \theta \dots \dots \dots (5)$$

In this equation, θ means the phase difference between force and velocity.

2.3 Analysis Method of Mechanical Power Factor

This subsection explains the analysis method of mechanical power factor from motion data. Unlike electrical system, some inputs of mechanical system are not periodical signal, namely distorted wave. Especially, human inputs are completely random. Therefore, Fourier transformation is necessary to decompose the distorted wave to components of sinusoidal wave. The procedure of the mechanical power factor analysis is shown below.

- (1) Obtain force and velocity in a motion.
- (2) Apply Discrete Fourier Transformation (DFT) to both force and velocity.
- (3) Derive the power factor.

In the second process, DFT is performed in short time period. By DFT, force and velocity can be expressed as (6) and (7).

$$f_{st} = F_{0,st} + \sum_{n=1}^N F_{mn,st} \sin(n\omega t + \theta_{F_{n,st}}), \dots \dots \dots (6)$$

$$\dot{x}_{st} = \dot{X}_{0,st} + \sum_{n=1}^N \dot{X}_{mn,st} \sin(n\omega t + \theta_{\dot{X}_{n,st}}), \dots \dots \dots (7)$$

Subscripts st and mn means the short time, and magnitude of n th frequency component respectively. N is maximum data number. ω and θ are angular velocity and phase. Active power is derived by,

$$P_{st} = \frac{1}{T} \int_0^T f_{st} \dot{x}_{st} dt \dots \dots \dots (8)$$

Apparent power is calculated from RMS value of force and velocity.

$$F_{n,st} = \frac{F_{mn,st}}{\sqrt{2}}, \dots \dots \dots (9)$$

$$\dot{X}_{n,st} = \frac{\dot{X}_{mn,st}}{\sqrt{2}}, \dots \dots \dots (10)$$

$$F_{rms,st} = \sqrt{F_{0,st}^2 + F_{1,st}^2 + \dots + F_{N,st}^2}, \dots \dots \dots (11)$$

$$\dot{X}_{rms,st} = \sqrt{\dot{X}_{0,st}^2 + \dot{X}_{1,st}^2 + \dots + \dot{X}_{N,st}^2}, \dots \dots \dots (12)$$

$$S_{st} = F_{rms,st} \dot{X}_{rms,st} \dots \dots \dots (13)$$

Finally, power factor in mechanical system is expressed by following equation.

$$MPF_{st} = \cos(\theta_{st}) = \frac{P_{st}}{S_{st}} \dots \dots \dots (14)$$

3. Power Factor Analysis Focusing on the Specific Frequency Component

In previous section, the power factor analysis method is described. However, this approach is not suitable for the unified

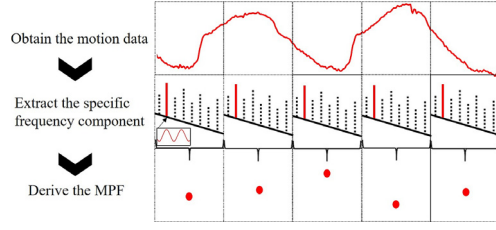


Fig. 2. Analysis method of *MPF* focusing on the fundamental frequency component

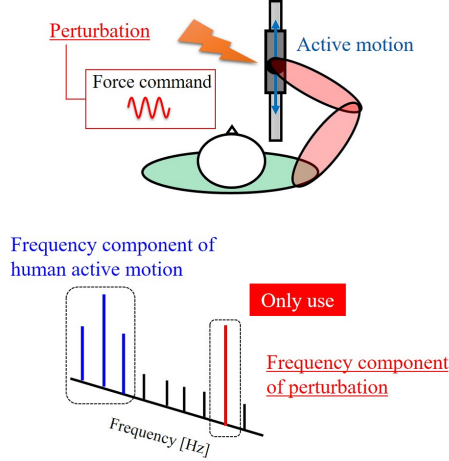


Fig. 3. Evaluation method of *MPF* in human active motion

evaluation of the body function, because the value of power factor depends on the trajectory of motion. Unlike the robot motion, human motion differs from person to person. In addition, in the situation that a robot adds the load to human motion, the energy of robot and human are mixed. In order to evaluate the power factor from the viewpoint of impedance, it is necessary to remove the influence on the power factor analysis by the trajectory of the active motion. Therefore, a new approach of power factor analysis is needed for the evaluation of human active motion. To solve this problem, new analysis method which focuses on the specific frequency component is proposed in this section (Fig. 2). In conventional method, all frequency components of motion are used for power factor analysis. On the other hand, in the new approach, the robot adds the perturbation which has specific frequency to human during active motion, and only specific frequency component is used for analysis (Fig. 3).

In proposed method, the specific frequency component is extracted by DFT. Force and velocity of specific frequency component are expressed as,

$$f_{sfc,st} = F_{m_sfc,st} \sin(n\omega t + \theta_{F_{sfc,st}}), \dots\dots\dots (15)$$

$$\dot{x}_{sfc,st} = \dot{X}_{m_sfc,st} \sin(n\omega t + \theta_{\dot{X}_{sfc,st}}), \dots\dots\dots (16)$$

Subscript *m_sfc* means the magnitude of specific frequency component. Active power is calculated from the time average of instantaneous power.

$$P_{sfc,st} = \frac{1}{T} \int_0^T f_{sfc,st} \dot{x}_{sfc,st} dt \dots\dots\dots (17)$$

Apparent power is calculated from RMS value of force and velocity.

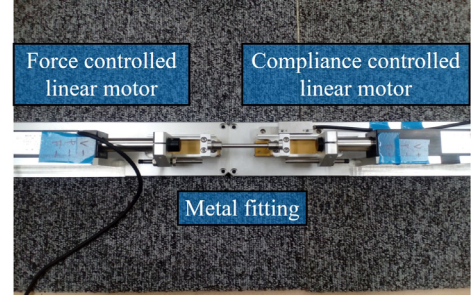


Fig. 4. Experimental setup in passive motion

$$F_{sfc,st} = \frac{F_{m_sfc,st}}{\sqrt{2}}, \dots\dots\dots (18)$$

$$\dot{X}_{sfc,st} = \frac{\dot{X}_{m_sfc,st}}{\sqrt{2}}, \dots\dots\dots (19)$$

$$F_{sfc,rms,st} = \sqrt{F_{sfc,st}^2}, \dots\dots\dots (20)$$

$$\dot{X}_{sfc,rms,st} = \sqrt{\dot{X}_{sfc,st}^2}, \dots\dots\dots (21)$$

$$S_{sfc,st} = F_{sfc,rms,st} \dot{X}_{sfc,rms,st} \dots\dots\dots (22)$$

Therefore, the mechanical power factor which only uses specific frequency component can be expressed by following equation.

$$MPF_{sfc,st} = \cos(\theta_{sfc,st}) = \frac{P_{sfc,st}}{S_{sfc,st}} \dots\dots\dots (23)$$

4. Experimental Verification

This section explains the experimental verification of the proposed method. Two kinds of experiments are conducted to verify the proposed analysis method. In the first experiment, passive motion is evaluated by the proposed analysis method. “Passive motion” means the situation which the robot adds the force unilaterally to human. On the other hand, in the second experiment, active motion is evaluated. “Active motion” means the situation which the human adds the force to the robot. Compliance controlled linear motor is used to simulate the state of upper limb in both experiment. The purpose of these experiment is to verify the integrity between the impedance and power factor.

4.1 Power Factor Analysis in Passive Motion

4.1.1 Experimental Setup In this experiment, two units of linear motor are used. Figure 4 shows the experimental setup. Metal fitting is used to connect the both linear motors. Force controlled motor which is commanded sinusoidal wave is used to push the environment. On the other hand, compliance controlled motor is used as environment. Block diagram and experimental parameters of compliance control and force control are shown in Fig. 5, Table 2 and Fig. 6, Table 3. Disturbance observer (DOB)⁽¹⁴⁾ is implemented to the system to ensure the robustness. Reaction force observer (RFOB)⁽¹⁵⁾ estimates the contact force during motion. Gains were determined by preliminary simulation and experiment. Cutoff frequency of DOB and RFOB are set to remove high frequency noise. Command of force is set to low frequency so as not to be affected by the cutoff frequency. Five conditions are set for the impedance value of compliance control,

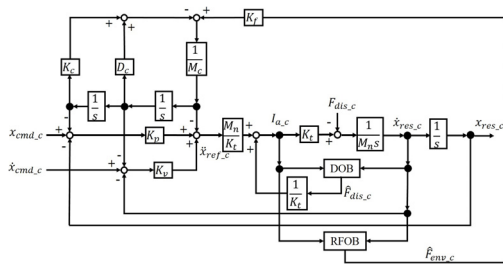


Fig. 5. Block diagram of compliance control

Table 2. Experimental parameters of compliance control in passive motion

Command of position $x_{cmd,\mathcal{F}}$	0.01 m
Command of velocity $\dot{x}_{cmd,\mathcal{F}}$	0.0 m/s
Force gain K_f	1.0
Position gain K_p	900
Velocity gain K_v	60
Thrust constant K_t	33 N/A
Nominal mass of motor M_n	0.50 kg
Virtual mass M_c	0.50 kg
Virtual damper D_c	30, 60, 100 Ns/m
Virtual spring K_c	225, 300, 400 N/m
Cut-off freq. of DOB	500 rad/s
Cut-off freq. of RFOB	500 rad/s

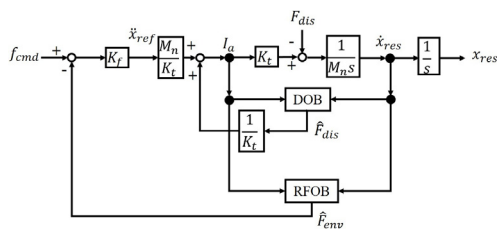


Fig. 6. Block diagram of force control

Table 3. Experimental parameters of force control in passive motion

Command of force f_{cmd}	5.0sin($2\pi ft$) N
Frequency of force command f	2.0 Hz
Cut-off freq. of DOB	500 rad/s
Cut-off freq. of RFOB	500 rad/s

Table 4. Analysis result of power factor in passive motion

Case	Impedance			MPF (Conventional method)		MPF (Proposed method)	
	M_c	D_c	K_c	Sim.	Exp.	Sim.	Exp.
1	0.2	30	225	0.88	0.66	0.88	0.90
2	0.2	60	225	0.96	0.71	0.96	0.97
3	0.2	100	225	0.98	0.75	0.98	0.99
4	0.2	30	300	0.80	0.65	0.80	0.82
5	0.2	30	400	0.70	0.59	0.70	0.72

and the consistency of impedance and power factor is verified.

In addition to the experiment, the contact force and velocity when force controlled motor touched impedance environments was simulated. Therefore, the power factor calculated from the simulation data and experimental data is compared.

4.1.2 Experimental Results Experimental result and simulation result of power factor in various impedance are shown in Table 4. In this table, experimental value and simulation value are the mean value of the power factor during motion for 20 seconds. Additionally, in the proposed method, only frequency component of command value of the force control is used for power factor analysis. In the viscous

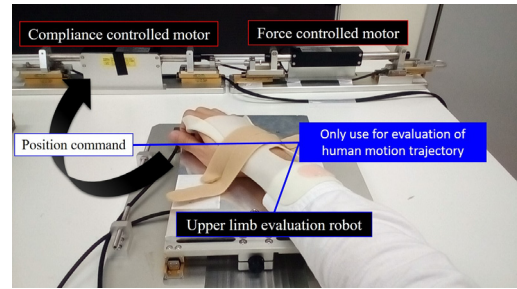


Fig.7. Experimental setup in active motion

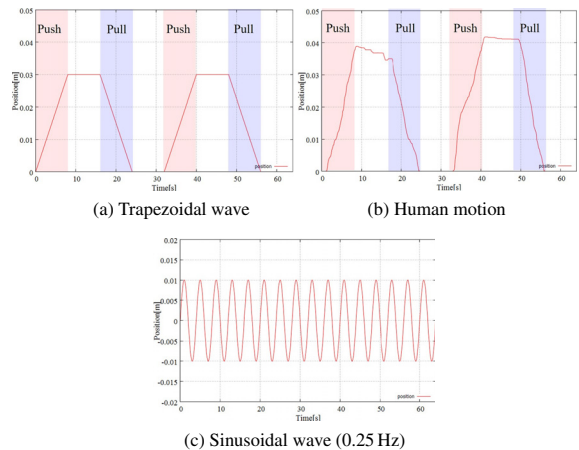


Fig. 8. Three types of position command

dominant situation (case3), it is confirmed that power factor is higher than the stiffness dominant situation (case1). Experimental results of the power factor which is analyzed by the conventional method are slightly different from simulation results. It is assumed that the harmonic component caused by the friction of the experimental components influenced the power factor analysis. On the other hand, in the proposed method, there is almost no difference between experimental results and simulation results. The results mean that the power factor in original motion can be obtained from the proposed method. From these results, it is suggested that the human active motion can be evaluated by using only the frequency component of perturbation which is intentionally given by the system.

4.2 Power Factor Analysis in Active Motion

4.2.1 Experimental Setup In this experiment, the power factor evaluation of active motion is verified by using two linear motors. Experimental setup is shown in Fig. 7. The basic configuration of the experimental setup is same as in the previous section. The compliance controlled motor is used to simulate a human limb. To verify the effects of trajectory, the position command of compliance control is set as Fig. 8. In the case of Fig. 8(a) and Fig. 8(c), the position command is designed by mathematical model. On the other hand, in the case of Fig. 8(b), the position command is generated by human motion trajectory. In human motion trajectory, the position command of compliance control is decided by the position information of upper limb evaluation robot. User operates the upper limb evaluation robot according to the experimental task (Table 5).

In addition, force controlled motor whose command is the sinusoidal wave is used as the evaluation system.

Table 5. Experimental task

Time[s]	Task
0-8	Push
8-16	Hold the current position
16-24	Pull
24-32	Hold the current position
32-40	Push
40-48	Hold the current position
48-56	Pull
56-64	Hold the current position

Table 6. Experimental parameters of force control in active motion

Command of force f_{cmd}	$3.0\sin(2\pi ft)+5.0\text{ N}$
Frequency of force command f	1.0 Hz
Cut-off freq. of DOB	500 rad/s
Cut-off freq. of RFOB	500 rad/s

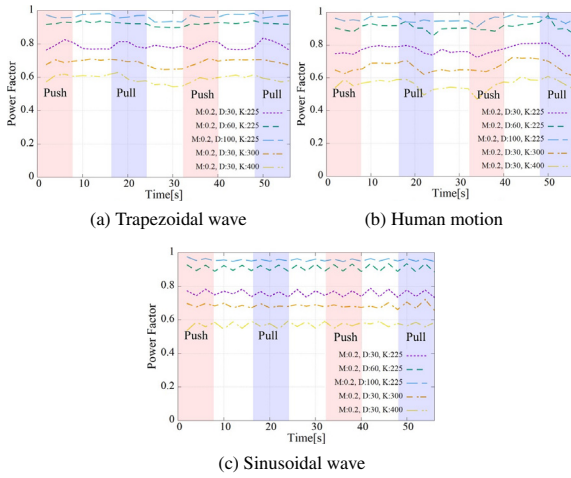


Fig. 9. Analysis result of power factor in active motion

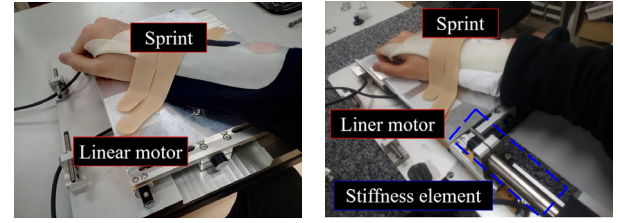
Experimental parameters of force control are shown in Table 6. By adding the perturbation of a specific frequency from force controlled motor, the power factor analysis which is independent from human motion trajectory is realized.

4.2.2 Experimental Results Figure 9 show the analysis result of the power factor in active motion. Same as previous experiment, the power factor in the viscous dominant situation is higher than the stiffness dominant situation. Therefore, the relationship between power factor and impedance is consistent without being influenced by trajectory of the evaluation object. However, the analysis result slightly fluctuated. It may be due to the inertia caused by active motion was influenced.

4.3 Experimental Evaluation of Upper Limb Function in Active Motion

4.3.1 Experimental Setup The power factor evaluation of upper limb function in active motion is verified by this experiment. In this experiment, the upper limb evaluation robot which is composed by the linear motor and a stiffness element is used to add the perturbation to upper limb (Fig. 10). Experimental parameters of force control of the upper limb evaluation robot are shown in Table 7.

In addition, power factor in the healthy state and the paralyzed state are compared. In the healthy state, a subject operates the evaluation robot in the relax state according to the experimental task (Table 5). On the other hand, in the paralyzed state, the subject operates the evaluation robot which



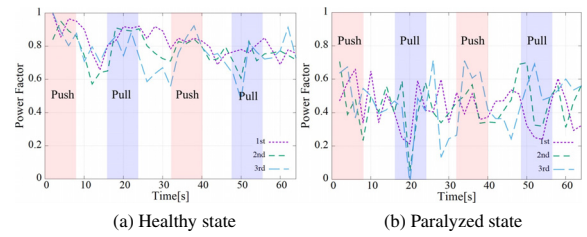
(a) Healthy state

(b) Paralyzed state

Fig. 10. Experimental setup

Table 7. Experimental parameters of force control of upper limb evaluation robot

Command of force f_{cmd}	$1.0\sin(2\pi ft)+3.0\text{ N}$
Frequency of force command f	1.0 Hz
Cut-off freq. of DOB	500 rad/s
Cut-off freq. of RFOB	500 rad/s



(a) Healthy state

(b) Paralyzed state

Fig. 11. Analysis result of power factor

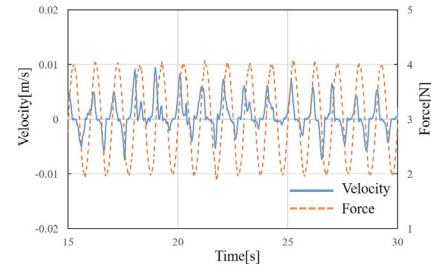


Fig. 12. Phase difference in paralyzed state (3rd)

is connected to the stiffness element. In this experiment, the compliance controlled motor is used as the stiffness element. Experimental parameters other than impedance of the compliance controlled motor are same as Table 2. Impedance value of compliance control is set as M_c : 0.5 kg, D_c : 0.0 Ns/m, K_c : 12000 N/m to simulate the paralyzed state.

4.3.2 Experimental Results Experimental results are shown in Fig. 11. In healthy state, power factor is around 0.8. On the other hand, in paralyzed state, power factor is around 0.5. Therefore, the relationship between power factor and impedance is consistent. However, analysis results fluctuated greatly. Main reason of the fluctuation of power factor is the dynamical change of impedance of upper limb in active motion. Figure 12 shows the phase difference between velocity and force in paralyzed state (3rd). The phase difference largely fluctuated because of the impedance changing of upper limb.

5. Conclusion

An evaluation method for upper limb active motion by mechanical power factor was investigated in this paper. In proposed method, the perturbation was added from the evaluation system to human active motion. The unified evaluation

which doesn't depend on the trajectory of the motion can be realized by only using the frequency component of perturbation. Experimental results almost supported the claim in the paper. Therefore, the evaluation of the impedance adjustment function of the body during active motion from the view point of power factor was realized. As the future works, the power factor evaluation for each muscle group based on the functional effective muscle theory is conducted.

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