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Original Article

Development of a method for measuring joint torque using an isokinetic machine

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ABSTRACT

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Objective: To develop a method to measure knee joint resistance torque during passive motion by using isokinetic equipment (e.g., the Biodex, Cybex, and Kin-Com).

Method: We used the Biodex System 3 isokinetic equipment in the present study. To determine the resistance torque in human knee joints, we first established a method to correct for the torque due to gravity and inertia, based on the angle, angular velocity, and torque output from this equipment. Thereafter, to estimate the active torque due to muscle contraction, we measured the electromyograph (EMG) signals and fitted a potentiometer on the driving arm of the Biodex to synchronize the EMG signals with the Biodex output.

Results: At the angle θ_0, and denoting the torque that occurs in the lower leg due to gravity as T_0, the torque due to gravity (T_g) at angle θ is given by $T_g=T_0\cos\theta/\cos\theta_0$. Denoting the moment of inertia of the lower leg as I and the angular acceleration as a, the torque caused by inertia (T_I) is given by $T_I=I\,a$. Letting the value of the torque that is output by the Biodex be T_{total}, the resistance torque caused by the subject (T) is given by $T=T_{total}-T_g-T_I$. The changes in T that occur simultaneously with the EMG signals indicate the active torque that is caused by muscle contraction.

Conclusion: We measured the resistance torque that occurred during passive joint motion by correcting for the angle, gravity, and inertia, based on the angle and torque that were output by the Biodex. The joint torque, angle, and EMG signals were measured simultaneously by monitoring the output of a potentiometer mounted on the arm of the Biodex.

Key words: joint stiffness, quantification, muscle tension, viscoelasticity, electromyogram

Introduction

In rehabilitation medicine, objectively evaluating aggravated muscle tension caused by central nervous system disorders or contracture due to disuse or immobility is a major issue in understanding the patient's condition and evaluating the outcome of rehabilitation. In clinical practice, muscle tension is often manually evaluated by an examiner; however, the values are on an ordinal scale, which complicates the evaluation of rehabilitation treatment.

Thus, in the present study, we established a method to quantify joint stiffness by using the Biodex System 3 (hereafter referred to as "Biodex"; Biodex Medical Systems Inc., NY; Figure 1), which is an isokinetic machine used for muscle-strengthening exercises and muscular strength measurements in many rehabilitation facilities. Here, we describe the method, and express joint stiffness as the joint resistance torque produced during passive motion.

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Table 1. Nomenclature

α	: knee angle when Biodex showed the torque of 0
I	: Inertia of subject
I^{W}	: Inertia of sandbag
T	: Resistive torque generated by knee joint
T_g	: Gravitational torque of subject
T_{g0}	: Gravitational torque of subject when lower leg is horizontal
$T_g{}^{W}$	: Gravitational torque of sandbag
$T_{g0}{}^{W}$	: Gravitational torque of sandbag when it is horizontal
T_I	: Inertial torque of subject
$T_I{}^{W}$	: Inertial torque of sandbag
T_{total}	: Output torque of subject
$T_{total}{}^{W}$	: Output torque of sandbag
θ	: Angle of Biodex arm
$\dot{\theta}$	: Velocity of Biodex arm
$\ddot{\theta}$	: Acceleration of Biodex arm

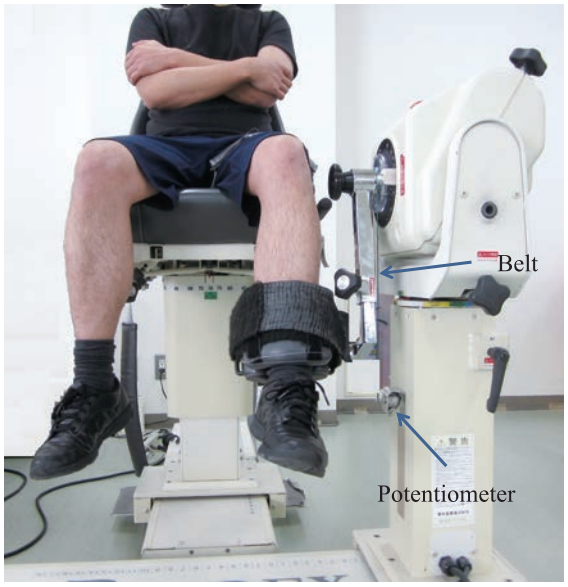

Figure 1. Setup of the Biodex.

1. Structural components of the joint

Joints comprise various passive viscoelastic components, including muscles, tendons, connective tissue, soft tissues, and contractile muscular components. With regard to the functional components of the muscle, they contain a cross-bridge structure that consists of actin and myosin as the contractile components and fasciae and tendons as the viscoelastic components. Furthermore, the flexibility of a muscle is defined in terms of compliance and stiffness (which is the inverse of compliance), as the ratio of the change in tension to the change in length [1]. As the muscle and surrounding tissues are viscoelastic, we assumed that the joints composed of these muscles and tissues also possess viscoelastic properties.

2. Pathogenesis of joint contracture

Joint contracture is evaluated by the amount of resistance exerted by the subject during passive movement. For muscles with increased tension, resistance torque is considered to be small during slow passive motion, although it increases during fast passive motion [2]. In recent years, this issue has received attention because changes in muscle tissue, such as muscle fibrosis and shortening caused by disuse or paralysis, affect both passive muscle resistance and active muscle activity [3].

Dietz et al. [4–6] classified the causes of muscle tension into reflex components, which originate from the stretch reflex, and non-reflex components, which are caused by resistance that arises due to the viscoelasticity of the tissues that comprise the joint. Furthermore, Sinkjaer et al. [7] classified the non-reflex components into cross-bridge structure components, which are characteristic of the muscles, and elastic components, such as tendons and fasciae. However, they did not conduct neurophysiological studies based on electromyographic monitoring. As the changes in the viscoelastic (non-reflex) components affect the extensibility (the amount of stretch during gentle and slow extension) and passivity (the resistance felt by the subject depending on the speed of the stretch) that occurs during passive motion of the joint, they are considered an important cause of hypertonia [3].

3. Evaluating joint contracture

An objective evaluation method is needed to elucidate the therapeutic effect of rehabilitation on joint contracture. Moreover, hypertonia is currently evaluated by using neurophysiological and biomechanical methods. In the neurophysiological evaluation method, the F wave and H-reflex are evaluated using electrophysiology techniques. The biomechanical evaluation method uses a pendulum test and the passive resistance torque during joint motion [8].

(1) Neurophysiological method

By using various spinal reflex measures (e.g., the H-reflex, F wave, and T wave), the electrophysiological method evaluates the manner of formation of neurological contractures that represent spasticity, depending on the physiological abnormalities [9]. Although these evaluations are important in understanding the mechanism of various medical treatments, such as nerve blocks or aural medication, they are not well correlated with the muscle tension that is measured by using the modified Ashworth and Tardieu scales [9–11].

(2) Biomechanical method

During the pendulum test, the muscle strength measurement device is set in a torque-free condition, and only the time course of the angle is measured.

However, during passive resistance torque testing, the muscle strength measurement device moves the lower leg at a constant angular velocity, and both the resistance torque and joint angle are measured. This method exhibits good correlation with the amount of clinical joint contracture [3].

Therefore, we decided to use the Biodex, which is routinely used in rehabilitation centers to measure the resistance torque due to passive motion. Moreover, we attempted to quantify the joint contractures. By simultaneously analyzing the surface electromyograph signals, we aimed to accurately capture the changes resulting from the muscle reflex and non-reflex components of the tissues surrounding the muscle and joint.

Methods and Subjects

1. Correction in the Biodex passive motion mode

During passive motion, the Biodex (Figure 1) operates over a given angular range at a given angular velocity, and outputs the torque applied on the axis of the rotation, the angle, and the angular velocity. By correcting for the torque due to angle, gravity, and inertia, the subject's joint resistance torque could be determined from the measured torque. In this scenario, the measured torque is the joint resistance torque combined with the torque due to gravity and the torque due to inertia, which we refer to as "total torque" (Figure 2).

(1) Angle correction

At the natural drooping position, the Biodex arm alone outputs 0° from its pivot. However, a small positive or negative value is output when the subject's lower leg is fixed to the Biodex arm. Therefore, when fixing the lower leg to the Biodex arm (without muscle contraction) and placing the arm in the natural drooping position, we set the knee joint angle to 0°. Specifically, we fixed the subject's lower leg to the Biodex arm that is used for the knee joint, and measured the knee joint angle (α), which produces a torque value of 0 in the muscle's non-contracted state. We then subtracted α from the angle displayed when the Biodex arm and the subject's lower leg were in the natural drooping position, and the resulting value was considered to be 0°.

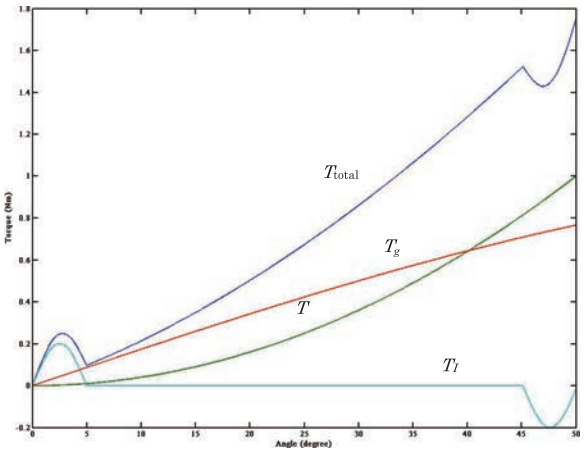

Figure 2. Schematic diagram of measured torque and its components (T_I is inertial torque, T_g is torque due to gravity, T is joint resistant torque, and T_{total} is the output of the Biodex. Therefore, T is obtained by subtracting T_g and T_I from T_{total}.)

(2) Correcting for the torque due to gravity

For gravity correction, we set the angle when the subject's lower leg was fixed to the arm (shown by the Biodex) as θ_0, and determined the torque without muscle contraction [$T_g(\theta_0)$]. Therefore, the torque due to gravity (T_{g0}) that occurs with the lower leg in the horizontal position was calculated as:

$$T_{g0} = T_g(\theta_0)/\cos(\theta_0+\alpha) \quad (1)$$

In addition, the torque due to gravity at the joint angle $\theta(t)$ [$T_g(t)$] becomes:

$$T_g(t) = T_{g0}\cos(\theta(t)+\alpha) \quad (2)$$

(3) Correcting for the torque due to inertia

To determine the moment of inertia of the lower leg, we fixed three 1-kg weights along the Biodex arm used for the knee joint, and the torque due to the inertia of the weight [$T_I^W(t)$] was calculated as:

$$T_I^W(t) = I^W\ddot{\theta}(t) \quad (3)$$

Thereafter, we performed extension and flexion motions with the Biodex arm by moving it back and forth twice in the high-speed passive-motion mode, using an angular velocity of 90°/s, and measured the resulting angle and torque of the arm. However, torque due to the extension was not present in the weights; therefore, we considered that the total torque output by the Biodex (T_{total}^W) only consisted of the torque due to gravity (T_g^W) and the torque due to inertia (T_I^W) (Equation 4). We determined the torque due to gravity in the weights ($T_g^W(t)$) by using Equations (1) and (2), and we obtained $\ddot{\theta}(t)$ by differentiating the angular velocity $\dot{\theta}$ that was output by the Biodex. After substituting $T_g^W(t)$ and $\ddot{\theta}(t)$ into Equation (4), we obtained I^W by using the least squares method.

$$\begin{aligned} T_{total}^W(t) &= T_I^W(t) + T_g^W(t) \\ &= I^W\ddot{\theta}(t) + T_{g0}^W\cos(\theta(t)+\alpha) \end{aligned} \quad (4)$$

Thereafter, to estimate the moment of inertia of the subject (I), we multiplied I^W by the ratio of T_{g0} to T_{g0}^W:

$$I = I^W T_{g0}/T_{g0}^W \quad (5)$$

To determine the torque due to inertia, we multiplied I by the angular acceleration $\ddot{\theta}$ (the derivative of $\dot{\theta}$ from the Biodex output):

$$T_I(t) = I\ddot{\theta}(t) \quad (6)$$

At each of the angles, we subtracted T_g and T_I from the torque that was output by the Biodex $T_{total}(t)$, and considered the resulting values to be the resistance torque of the subject's muscle strength [$T(t)$]:

$$T(t) = T_{total}(t) - T_{g0}\cos\theta(t) - I\ddot{\theta}(t) \quad (7)$$

2. Subjects and their positions

One able-bodied individual and one stroke patient were included in this study. The subjects sat in the Biodex, their trunk was fixed with a seat belt, and we fixed the center of the measured knee joint to the axis of rotation of the Biodex arm. Thereafter, we adjusted the arm length to match the length of the subject's lower leg. For the electromyograph measurements, the subject's skin was pretreated and we attached electrodes (Vitrode V disposable electrodes, Nihon Kohden Corporation, Japan) at intervals of 2 cm. These electrodes were connected to the transmitter of the telemetry electromyograph unit (MQ16, Kissei Comtec Co., Ltd., Japan), and the data was wirelessly transferred from the transmitter to a receiver that was attached to a personal computer via a USB port.

In the passive motion mode, we moved the knee joint from the natural drooping position (90° knee flexion) to 40° knee flexion, with the angular velocity set at 90°/s (the maximum angular velocity of the Biodex). We recorded a time series of values for resistance torque and angle at a sampling frequency of 100 Hz during the movement. Simultaneously, we recorded the electromyograph signals at a sampling frequency of 1 kHz, and we removed the noise from the electromyograph unit by using an AC filter and a 10- to 350-Hz bandpass filter.

Results

1. Correction method

First, we determined the moment of inertia I^W of a 3-kg weight that simulated the lower leg. For angle correction while the weight was being fixed, we set the value α=0°, as the torque was 0 when the Biodex arm was vertical. In addition, the torque due to gravity was 7.3 Nm when the arm angle was 53°. Using Equation (1), the torque of the weight due to gravity in the horizontal position was calculated to be:

$$T_{g0}{}^W = 7.3\ \text{Nm}/\cos(53^\circ - 0^\circ) = 12.13\ \text{Nm}$$

Thereafter, we determined $T_I{}^W$ by using Equation (4) with $T_g{}^W$ and $T_{total}{}^W$ that were output by the Biodex when the weights were applied. We then substituted $T_I{}^W$ and $\ddot{\theta}(t)$ into Equation (3) and estimated $T^W(t)$ by using the least squares method, which provided a value of 0.485 kgm². This allowed us to use Equation (4) to obtain:

$$T^W{}_{total}(t) - T_I{}^W - T_g{}^W$$

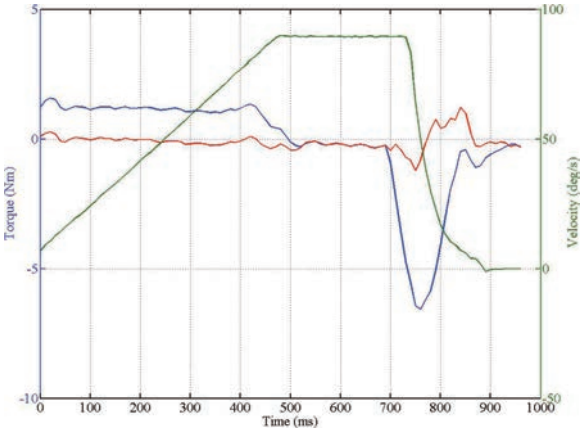

Figure 3. Torque obtained by correction of inertial torque.
green: angular velocity, blue: torque before correcting an inertial torque, red: torque after correcting inertial torque, which is almost 0.

As muscle strength and joint viscoelasticity are not present in the weights, the expected value of the formula above is 0.

Figure 3 shows the torque values before (blue) and after (red) correcting for the angular velocity and inertia when using the weights. Figure 3 shows that the torque generated during the turn from extension to flexion is corrected, and the resulting value was almost 0.

Thereafter, we calculated the experimental values for the two subjects. The subjects' moment of inertia was determined using Equation (5), as expressed by:

$$0.485\ \text{kgm}^2 \times 18.4\ \text{Nm}/12.13\ \text{Nm} = 0.739\ \text{kgm}^2$$

We then determined the angular acceleration by differentiating the angular velocity that was output from the Biodex, and multiplied the acceleration by the moment of inertia to determine the torque due to inertia. As shown in Equation (7), the joint resistance torque is calculated by subtracting the torque due to gravity and inertia from the torque output by the Biodex; thus, we used this equation to determine the joint resistance torque at each angle.

Figure 4 shows the knee joint angle (vertical position is regarded as 0°), the knee joint resistance torque (upwards torque acting in the direction of the knee extension), and the electromyogram of a healthy subject's quadriceps and hamstrings. The Biodex arm did not move until 400 ms, at which point it began moving and remained at 50°until 1,130 ms, thus providing a mean angular velocity of 68°/s. The maximum velocity was 90°/s, which occurred between 600 and 900 ms. The joint resistance torque increased along with the extension of the knee joint, and no muscular activity was observed for the healthy subject's quadriceps and hamstrings.

Figure 5 shows the knee joint angle, knee joint

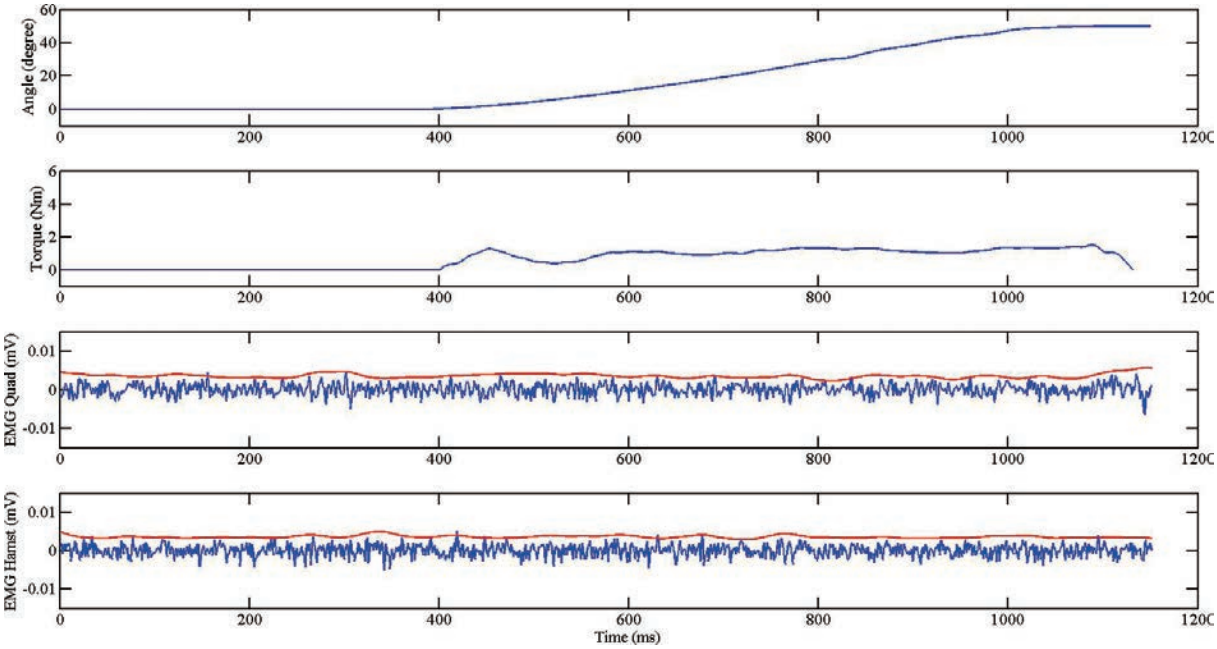

Figure 4. Angle, torque, EMG of quadriceps femoris muscle and EMG of hamstrings muscle of an able-bodied individual are shown in the four panels from top to bottom. The root mean squares of the EMGs are scaled by three times the actual magnitude and shown in red to avoid superposition.

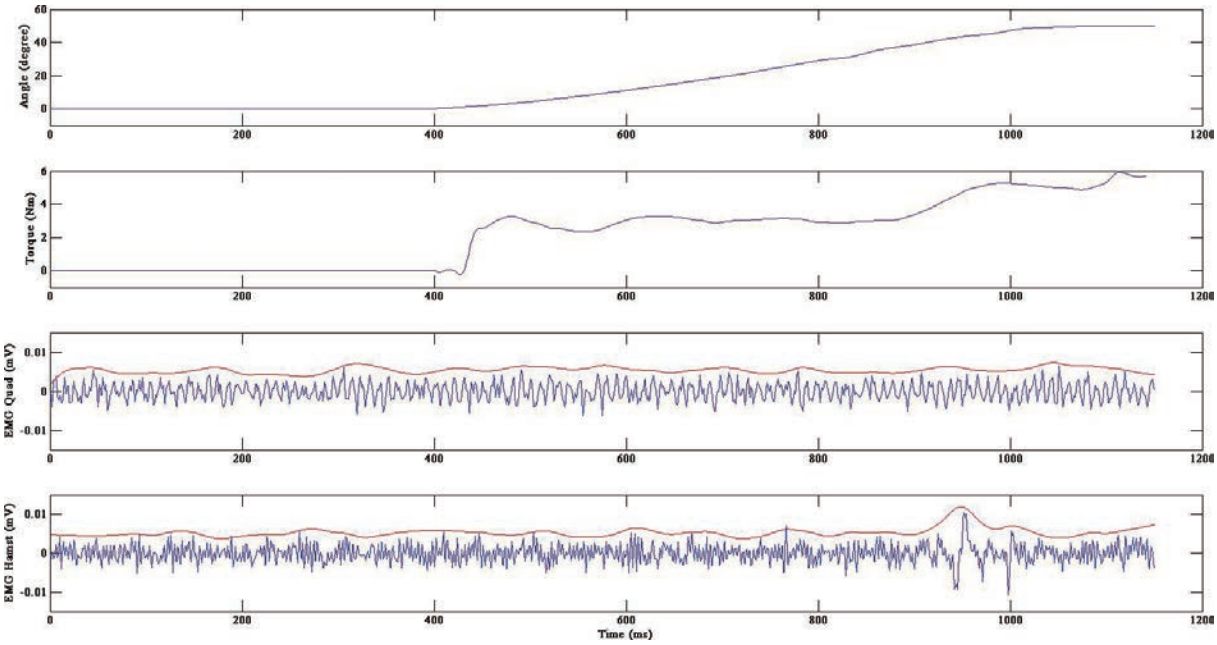

Figure 5. Angle, torque, EMG of quadriceps femoris muscle and EMG of hamstrings muscle of a spastic patient are shown in the four panels from top to bottom. Root mean squares of the EMGs are scaled by three times the actual magnitude and shown in red to avoid superposition.

resistance torque, and electromyogram of the stroke patient's quadriceps and hamstrings. Muscular activity was observed in the stroke patient's hamstrings at approximately 900 ms, and the joint resistance torque increased along with the extension of the knee joint. No muscular activity was observed in the stroke patient's quadriceps.

Discussion

As we could not measure the weight of the leg using the Biodex's passive motion mode, we measured the weight using the isokinetic mode. After changing to the passive motion mode, we then measured the torque during knee extension. After calculating the torque

due to gravity and inertia, and removing it from the torque output by the Biodex, we were able to measure the torque that occurred in the knee joint muscles and surrounding soft tissues during knee joint extension.

Joint torque is thought to increase when muscle contraction is aggravated (e.g., due to stroke), and the causes for this increase can be divided into muscular reflex and non-reflex components in the muscle and tissues surrounding the joint [12]. When the reflex components are strong, treatment such as anti-spasticity medication or nerve blocks should be selected. However, when the non-reflex components are strong, treatment such as joint mobilization or continuous muscle stretching should be selected. Based on our newly developed measurement method, appropriate treatment can be administered to patients based on their individual condition.

In the future, we hope to use this joint torque measurement method to determine the temporal changes in muscle tension, or to evaluate the hyperactivity of muscle torque before and after nerve blocks, and quantitatively evaluate the nerve block effect.

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