INTRODUCTION

A problematic postural balance influences the stability of the COG (Center of Body Gravity) fluctuation, i.e., the feedback control movement in maintenance of the walking sequence. Measuring instruments were developed for acquiring time series data of movement of COG and both hips, which are portable, wearable PC-assisted (WPC), and employed one gyro sensor and two accelerometers.

The fluctuation of movement, i.e., the feedback control movement of left and right legs in the walking sequence, becomes less stable under the influence of a problem to part of the lower limb or back. CCD video cameras have been used for the 3-D measurement of human movement. However, there are some problems: the measured distance is not enough for the walking analysis because cameras are fixed at one place, and it is necessary to process many images. Also sometimes markers on joints disappear because of the camera angles in walking.

For medical evaluation in rehabilitation, it is expected to measure without cords in order to enable some extent of the walking distance and to allow ascending and descending of stairs in daily movement. This problem was analysed on the basis of two new approaches. The first approach is a newly developed measurement system of human movement - a small wearable personal computer (WPC)–assisted system consisting of two accelerometers or a gyro sensor. While walking or standing, the WPC is worn on a subject’s wrist, the sensors are fixed to a subject’s left and right hip or back, and batteries are inserted into a subject’s waist pouch. The time series data of accelerations in three axes of both the subject’s hip or three angles of the back motion are recorded into the WPC while walking.

However, it is difficult to analyse directly the characteristics of movement stability using the raw serial measurement data because of their complex fluctuations in feedback control movement among the variables. The second approach therefore is an analysis of impulse response or power spectrum using autoregressive (AR) modelling. AR modelling defines the best prediction given the power spectral density, which expresses the characteristics of a sequential system concisely, and decomposing it into periodic components.

An analysis of impulse response was done with a particular focus on the feedback control movement: the movement of left and right knees in walking balance.

METHODS

Measurement System using two Accelerometers

This system consists of two three-axis accelerometers (Akebono Brake Co. Ltd.) that are connected easily to a micro PC. While walking, the sensors are fixed to the subject’s left and right sides of the hip, and the micro PC and batteries are inserted into a subject’s waist pouch. When a switch is turned on, the serial accelerations in three axes of both the subject’s hips are recorded into the EPROM at 15 Hz (Figure 1).

Measurement System using Gyro Sensor

This system consists of a MAXCUBE gyro sensor and a WPC (Figure 2). When a switch is turned on, the calibration of MAXCUBE gyro sensor starts before measurements are taken. After 20 minutes, an end sign appears, and the measurement starts by pushing a button of WPC. The angular displacement and the serial time count is zeroed after calibration. When a switch is turned on, the serial time count and the relative three angles, i.e., roll, pitch and yaw measures of the patient’s back are recorded into the WPC at 30 Hz. They are also displayed on a liquid crystal display on the WPC.
Spectral Analysis using AR modeling

Multivariate autoregressive (AR) modeling is given by (1),

\[ x_i(s) = \sum_{j=1}^{K} \sum_{m=1}^{M} a_{ij}(m)x_j(s-m) + u_i(s) \]  

where

- \( x_i(s) \) = stationary time series
- \( x_j(s-m) \) = past observed data
- \( u_i(s) \) = white noise
- \( a_{ij}(m) \) = AR coefficient

The frequency response function \( a_{ij}(f) \) of \( x_i(s) \) to the input \( x_j(s) \) is given by (2).

\[ a_{ij}(f) = \sum_{m=1}^{M} a_{ij}(m)e^{-i2\pi fm} \]  

where \( e^{-i2\pi fm} \) is Fourier transform of frequency response.

The system given by (1) is a feedback system within which \( x_j(s) \) is connected to \( x_i(s) \) by an element having the frequency response function \( a_{ij}(f) \) and each \( x_i(s) \) has its own noise source \( u_i(s) \)'s. Thus, \( x_i(s) \) can be expressed as a sum of the influences of \( u_i(s) \)'s. The estimate of the power spectral density \( p(f) \) is given by (3).

\[ p(f) = \frac{\sigma^2(M)}{\left| 1 - \sum_{m=1}^{M} a(m)e^{-i2\pi fm} \right|^2} \]  

where \( \sigma^2(M) \) is covariance.

This formula defines the best prediction, giving the power spectral density, which expresses the characteristics of a sequential system concisely, decomposing it into periodic components.

RESULTS AND DISCUSSION

Homeostasis is maintained in the human body. While walking, the movement of the left leg (left side of the hip) controls that of right leg (right side of the hip), and vice versa. This is a feedback control loop of two variables.

The computational impulse of two times the standard deviation (S.D.) of fluctuation of each subject’s hip movement was applied as white noise in this study. When the impulse is given to the left side of the hip movement, it is transmitted and its response appears on the right side of the hip movement, and vice versa.

Biomechanical analysis of fluctuation of COG while walking

Normal students (n=20, 20 yrs old, female) were selected as subjects. They suffered no orthopaedic problem or lower limb disorders. While walking, 20% of the subjects showed rhythmic fluctuations of the COG in roll, pitch, yaw (Figure 3a), but the remaining 80% did not display any non-rhythmic fluctuations of the COG in roll, pitch, yaw (Figure 3b).

For those with non-rhythmic fluctuations their abdominal or back muscles were weak, and they had a slight sway back, i.e., exaggerated lumbar lordosis, or pelvic obliquity. After they understood how to assume the correct posture, and had exercised the relevant muscle, their fluctuations of the COG and both sides of the hip became better and more rhythmic while walking.

The computational impulse of twice the standard deviation (S.D.) of the fluctuation of each subject’s hip movement was applied as white noise. When the impulse is given to left side of the hip movement, it is transmitted and its response appears on the right side of hip movement (L-R), and vice versa (R-L).
The value and duration of the impulse response of left side of the hip are larger than that of the right one (Figure 4a L-R<R-L).

Again, after they understood the correct posture, and exercised, both values of the impulse responses of both sides of the hip became similar to each other (Figure 4b L-R=R-L).

If the impulse response is checked regularly in the rehabilitation process, it will allow us to make a new evaluations of walking stability. The impulse response analysis on walking stability suggests a new potential for the understanding of medical recovery.

The stability of COG is representative of human movement balance and the power spectral analysis utilizing AR modelling provides clear results for the medical evaluation of human movement. It is well known that the $1/f^3$ fluctuation, i.e., an index of stable walking, decreased if the subjects had a high pulse rate or strong breathing as a result of stress.

**REFERENCES**


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