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Analysis of Angular Changes of Extremity Joints and Body Rotation in Normal and Pathological Walking by Normalized Pattern

Hirotaka IWANAGA

Department of Orthopaedic Surgery
Nagasaki University School of Medicine,
Japan

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INTRODUCTION

Recent advances in the treatment of patients with locomotor disturbances have emphasized the need for a better and more practical method to evaluate the progress of therapy. However, there have been very few reports evaluating the gait, as this may be time consuming, requiring the measurement of the angles of every joint.

Photographic methods of recording the serial displacements of locomotion had been developed by MUYBRIDGE.[11] MAREY first, and later BRAUNE and FISCHER perfected and applied this method to human gait. In the 1940's EBERHART *et al.* reported that the movement of the lower extremities and pelvis were clearly identified by this method. MURRAY *et al.*,[7][8] in the 1960's, conducted studies for the mean patterns of angular changes of normal subjects and established standards of normal variability by this method.

The previous methods for the presentation of the angular changes were divided roughly into two types; the angle-time diagram and the angle-angle diagram. The angle-time diagram is a method represented by the mean patterns of MURRAY (1964).[7] The angle-angle diagram introduced by GRIEVE (1968)[3] is formed by the angles of the two different joints to be plotted against each other.

We attempted to normalize the mean angular changes in the angle-time diagram.

The purpose of this study is to examine the efficiency of the normalized pattern of angular changes and to apply this method to the clinical examination.

Special attention was given to the small angular changes, especially those of the shoulder girdle and pelvis.

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SUBJECTS AND METHODS

Five normal adults and ten patients were enlisted for this study. The patients suffered from osteoarthritis (OA) of the hip, knee or ankle joint, anterior cruciate ligament insufficiency (ACLI), hemiplegia, parkinsonism and spinal disorders (Table 1).

The examinees were bare-footed and unclothed. The shoulder, elbow, wrist, hip, knee, ankle and fifth metatarso-phalangeal (MTP) joints were marked with white dots (9 mm in diameter) on their lateral sides. Besides, white tapes (10mm in width) were attached to the lateral sides of their extremities along longitudinal axes (Figure 1 (Ⅱ)).

Small electric lamps were placed on the superior parts of their shoulder girdle, showing rotation of the trunk. On the centers of the sacrum and pubic symphysis, short white sticks were fixed with velcrotape, perpendicular to the body surfaces, showing rotation of the pelvis. The motion of the shoulder girdle and pelvis could be observed through a mirror situated above the walking platform.

The two copper boards (25cm in width and 3m in length) were placed on the platform in parallel.

In order to differentiate the stance phase from the swing phase, an electric circuit, composed of the examinee's body and a wire connecting the copper board to the examinee's neck, was made to be closed by sole contact with the copper board. Two small electric lamps attached to the lateral side of the head were activated with relay switches (Figure 1 (Ⅰ)). The two lamps were used to indicate each sole contact. Double spots represented double support and single spots represented single support by the legs. Using this system, one walking cycle could be divided into four phases (phase Ⅰ to Ⅳ) according to the DUCROQUET's classification[2] (Figure 2).

NORMAL ADULT	5 CASES
OSTEOARTHRITIS THE HIP JOINT THE KNEE JOINT THE ANKLE JOINT	 1 CASE 1 CASE 1 CASE
ANTERIOR CRUCIATE LIGAMENT INSUFFICIENCY	1 CASE
HEMIPLEGIA	2 CASES
PARKINSONISM	2 CASES
ANKYLOSING SPONDYLITIS	1 CASE
LUMBAR DISC HERNIATION	1 CASE

Table 1. Subjects. (five normal adults and ten patients).

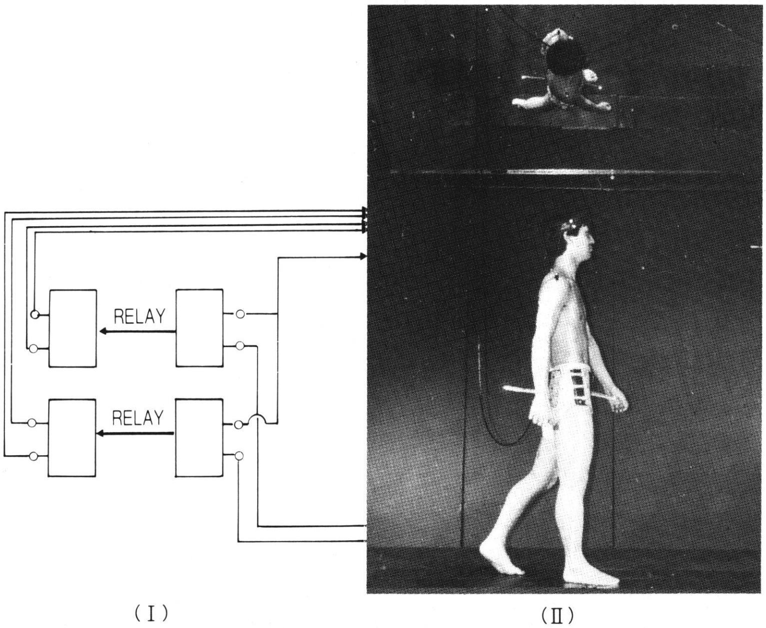

Fig. 1. (I) Diagram of the sole contact switches and stick-pictures of the sole contact signals.
(II) An examinee on the platform.

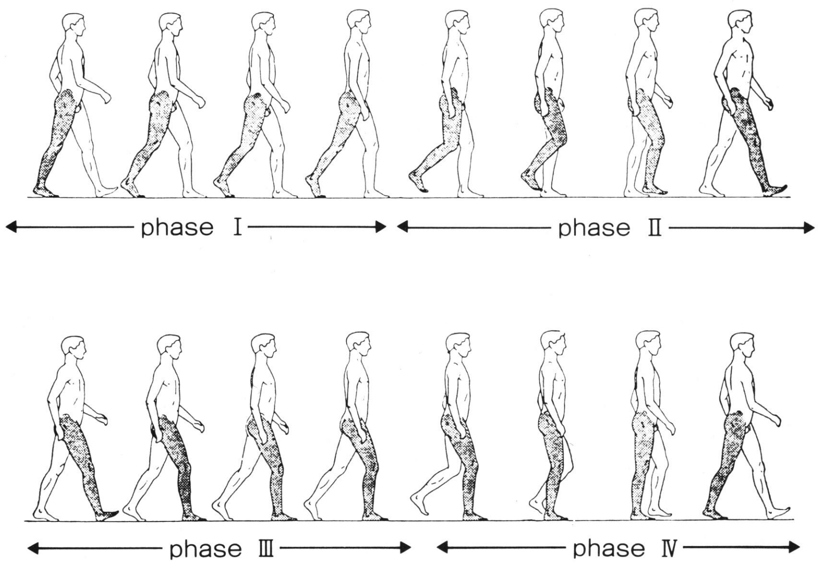

Fig. 2. DUCROQUET's Classification.
phase I : double posterior support of thrust.
II: oscillating period or levitation.
III: double anterior support of reception.
IV: unilateral support.
(Redrawn from DUCROQUET, R., DUCROQUET, J., and DUCROQUET, P. La Marche et les Boiteries, Paris, 34-35, 1965.)

The examinees were askek to walk customarily in groups of five in trials on the platform in front of a black screen. Their serial stick-pictures were taken from lateral and upper sides simultaneously, on long running film (ASA 400, FUJI FILM, TOKYO, JAPAN) with a stick-picture camera (OOSAWA Corp., TOKYO, JAPAN) (Figure 3). The camera was about 7m from the examinee, and exposed 24 pictures per second.

In each frame of the serial stick-pictures, angles of the shoulder girdle, shoulder joint, elbow joint, hip joint, pelvis, knee joint, ankle joint and MTP joint were measured using a pen digitizer (YODOBASHI computer union, TOKYO, JAPAN). The method of measuring the angle is shown in Figure 4. The direction of the arrows indicates a plus sign. The rotation of the anterior aspect of the shoulder girdle and pelvis to the right was called clockwise rotation; the rotation to the left, counterclockwise rotation.

The number of frames (measuring points) obtained in each walking cycle varied. The number of measuring points was adjusted to the median in five walking cycles, and angles of each measuring point were then calculated. In this manner, the mean patterns and the standard deviation of angular changes of a subject were obtained.

Secondly, the normalized angular changes were expressed throughout one walking cycle as a percentage of the difference between the maximum value and the minimum value of angular changes in each joint. When the maximum and minimum values of the angular changes were termed Y_1 and Y_2 respectively, the normalized angular change for Y was given by $\frac{Y}{Y_1\text{-}Y_2} \times 100$ (%).

The mean patterns and normalized patterns of angular changes of five walking cycles were calculated and illustrated on a computer (PC-9801, NEC, TOKYO, JAPAN).

The characteristics of the normalized patterns were examined by applying them to the clinical examination.

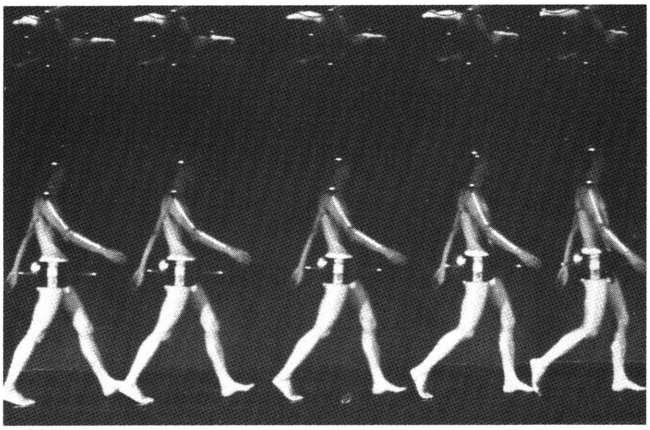

Fig. 3. Stick-pictures taken by a stick-picture camera.

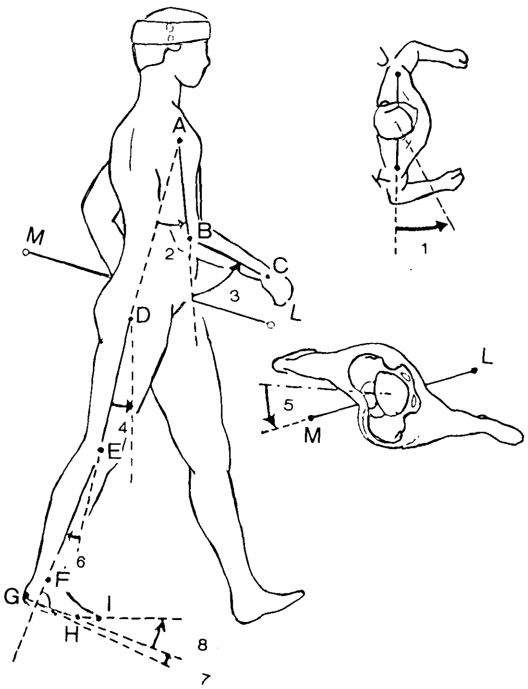

Fig. 4. Method of measuring the angle.
A: shoulder joint, B: elbow joint
C: wrist joint, D: hip joint
E: knee joint, F: ankle joint
G: posterior edge of heel, H: fifth MTP joint
I: toe tip, J: superior part of left shoulder girdle
K: superior part of right shoulder girdle
L: pubic symphysis, M: sacrum

1: shoulder girdle, 2: shoulder joint
3: elbow joint, 4: hip joint
5: pelvis, 6: knee joint
7: ankle joint, 8: MPT joint

RESULTS

1. Mean Pattern

The mean patterns of angular changes of a typical normal subject are shown in Figure 5.

The shoulder girdle rotated in counterclockwise and clockwise directions during each walking cycle, but on the other hand the pelvis rotated in clockwise and counterclockwise directions opposite to the shoulder girdle. The average maximum rotation of the shoulder girdle and pelvis were 7.1 ± 2.2 degrees and 17.0 ± 2.2 degrees respectively.

The shoulder and elbow joints showed one flexion movement and one extension

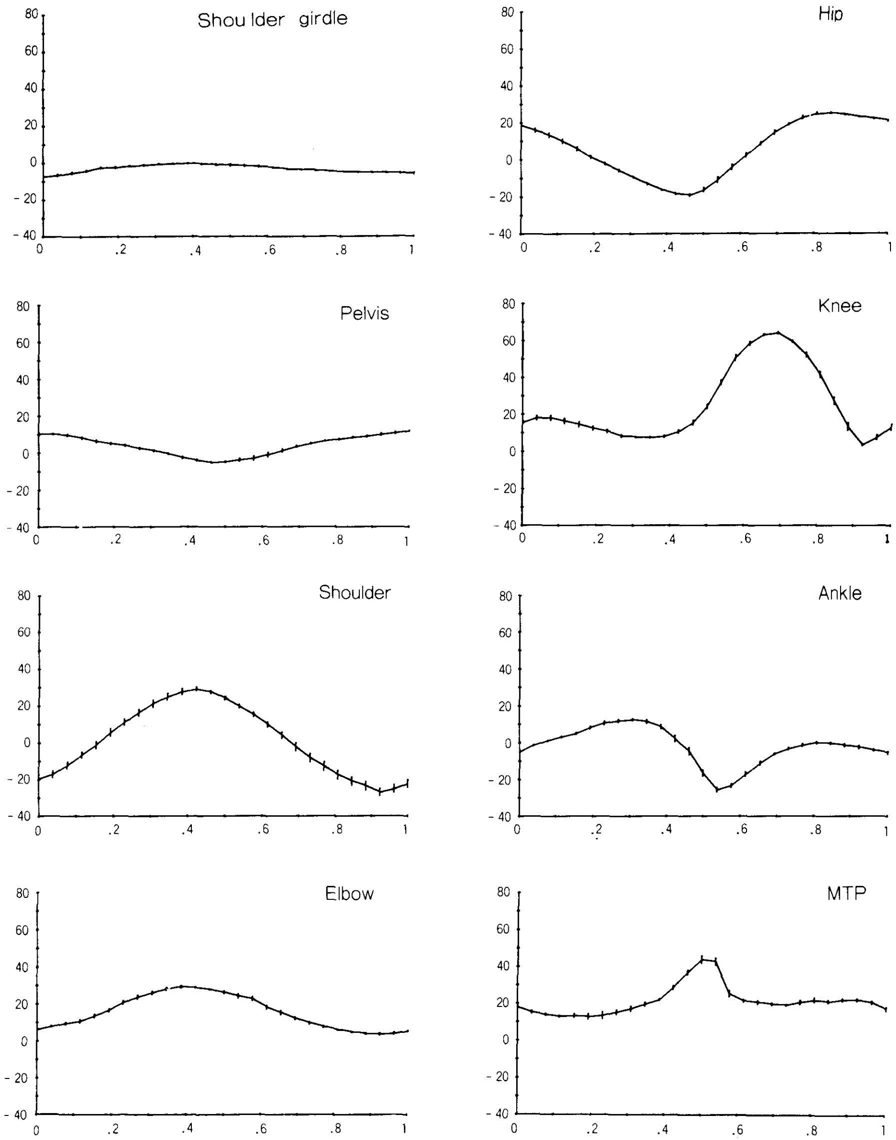

Fig. 5. Mean angular changes (Mean patterns) of the extremity joints and body rotation in a normal subject.
The X-axis consists of one walking cycle.
The Y-axis consists of angular changes.

movement during each walding cycle. The average maximum rotation of the shoulder and elbow joints were 56.2±7.5 degrees and 25.5±3.6 degrees respectively. The mean peak degree of shoulder flexion was 29.1±2.6 degrees in the latter third of phase Ⅳ, and shoulder extension was 27.1±4.9 degrees in the latter third of phase Ⅱ. The mean peak degree of elbow flexion was 29.0±1.8 degrees in the latter third of phase Ⅳ, and elbow extension was 3.5±1.8 degrees in the latter third of phase Ⅱ.

The hip joint showed one extension movement and one flexion movement during each walking cycle. On the other hand, the knee, ankle and MTP joints showed two waves of flexion and two of extension during each walking cycle. The average maximum rotation of the hip, knee, ankle and MTP joints were 44.5±3.0 degrees, 60.8±3.1 degrees, 38.1±4.7 degrees and 31.0±6.0 degrees respectively. The mean peak degree of hip extension was 19.2±1.9 degrees in the latter third of phase Ⅳ, and hip flexion was 25.3±1.1 degrees in the middle third of phase Ⅱ. The mean peak degree of knee flexion was 64.3±1.7 degrees in the first third of phase Ⅱ, and knee extension was 3.6±1.4 degrees in the latter third of phase Ⅱ. The mean peak degree of ankle extension was 12.4±1.6 degrees in the middle third of phase Ⅳ, and ankle flexion was 25.7±3.2 degrees in the first third of phase Ⅰ. The mean peak degree of MTP flexion was 12.9±1.3 degrees in the first third of phase Ⅳ, and MTP extension was 44.0±4.8 degrees in the latter third of phase Ⅳ.

In the patients, the average maximum rotation of each joint was smaller than that in a normal subject, especially in the shoulder girdle and pelvis where the average maximum rotation even in the normal subject was very small.

2. Normalized Pattern

The normalized patterns of angular changes of a normal subject are shown in Figure 6. The normalized patterns of the shoulder girdle, the shoulder and elbow joints were of the convex type. The pelvis and hip joint, however, were of the concave type. The ankle and MTP joints showed a two-peak pattern. The ankle joint showed a higher peak in the first half of the walking cycle, while the MTP joint showed a higher one in the middle phase of the walking cycle. The knee joint showed a smooth lower curve in the first half of the walking cycle and a higher one in the latter half.

In th patients, except for the hemiplegic patient at BRUNNSTROM's Stage Ⅳ, the shoulder, elbow, hip, knee, ankle and MTP joints showed a similar pattern to a normal subject. On the other hand, the shoulder girdle and pelvis showed a different pattern from a normal subject in the hemiplegic patients and patients with parkinsonism.

The normalized patterns of the shoulder girdle and pelvis in a normal subject, the hemiplegic patients (BRUNNSTROM's Stage Ⅳ and Ⅵ) and patients with parkinsonism (YAHR's Stage 3 and 4) are shown in Figure 7 to 9. The transverse rotation of the shoulder girdle and pelvis in a normal subject twisted in the opposite direction to each other during each walking cycle (Figure 7 (Ⅱ)).

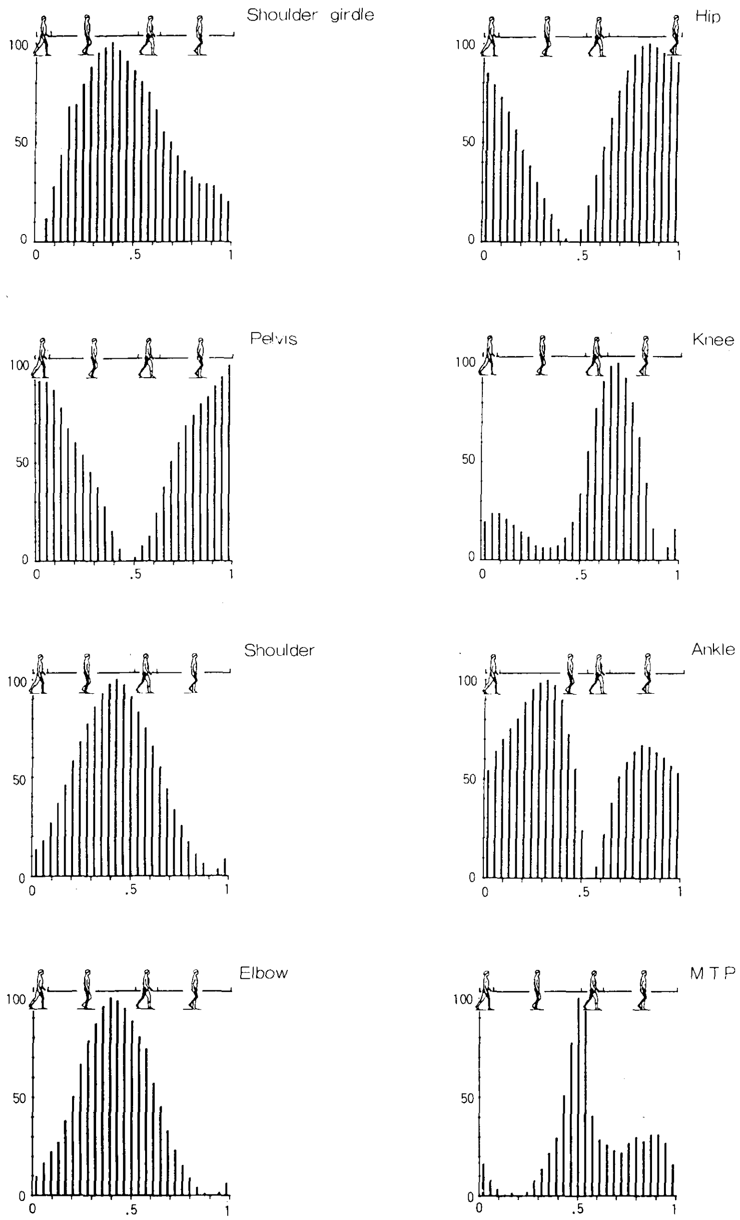

Fig. 6. Normalized angular changes (Normalized patterns) of the extremity joints and body rotation in a normal subject. The X-axis consists of one walking cycle. The Y-axis consists of normalized angular changes, being expressed as a percentage.

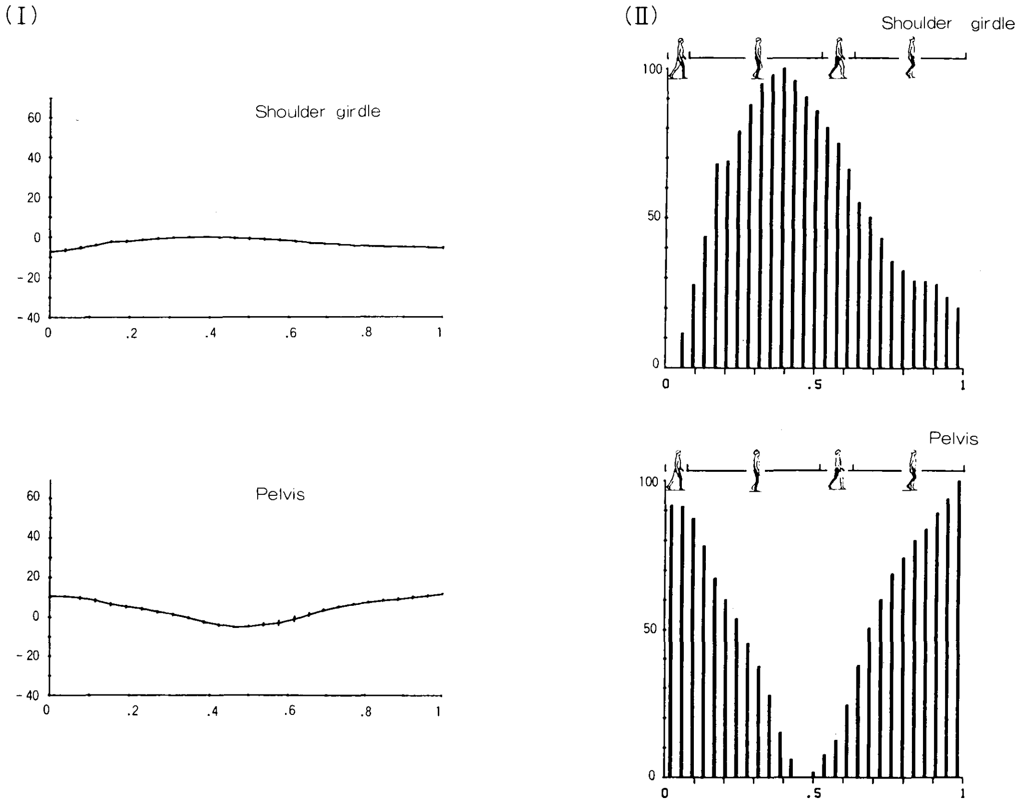

Fig. 7. (I) Mean patterns of the shoulder girdle and pelvis in a normal subject.
(II) Normalized patterns of the shoulder girdle and pelvis in a normal subject.

In the hemiplegic patient at Stage Ⅳ, the rotation of the shoulder girdle and pelvis twisted in the opposite direction in the first quarter of the walking cycle. In the latter three quarters, however, they twisted in almost the same direction (Figure 8 (A-Ⅱ)). On the other hand, in the patient at Stage Ⅵ, the rotation twisted in the opposite direction throughout one walking cycle (Figure 8 (B-Ⅱ)).

In the patient with parkinsonism at Stage 4, the rotation of the shoulder girdle and pelvis twisted in almost the same direction throughout one walking cycle (Figure 9 (C-Ⅱ)). On the other hand, in the patient at Stage 3, the rotation twisted in the opposite direction in the first quarter of the walking cycle and in the same direction in the latter three quarters (Figure 9 (D-Ⅱ)).

The number of bars and the cadence in a typical normal subject and ten patients are shown in Table 2. Secondly, the normalized patterns of the knee joint in a normal subjent, the patient with ACLI and the hemiplegic patient at BRUNNSTROM's Stage Ⅳ are shown in

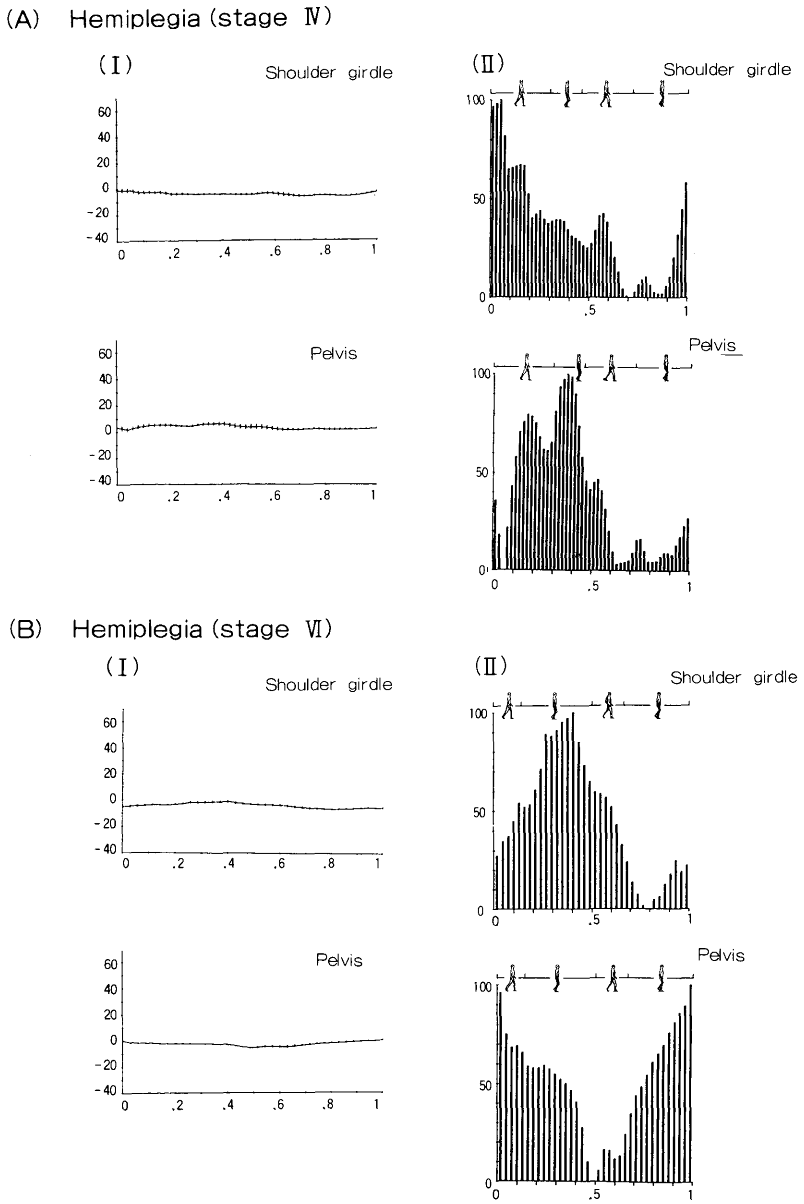

Fig. 8. (Ⅰ) Mean patterns of the shoulder girdle and pelvis in the hemiplegic patients at BRUNNSTROM's Stage Ⅳ (A-Ⅰ) and Stage Ⅵ (B-Ⅰ).
(Ⅱ) Normalized patterns of the shoulder girdle and pelvis in the hemiplegic patients at BRUNNSTROM's Stage Ⅳ (A-Ⅱ) and Stage Ⅵ (B-Ⅱ).

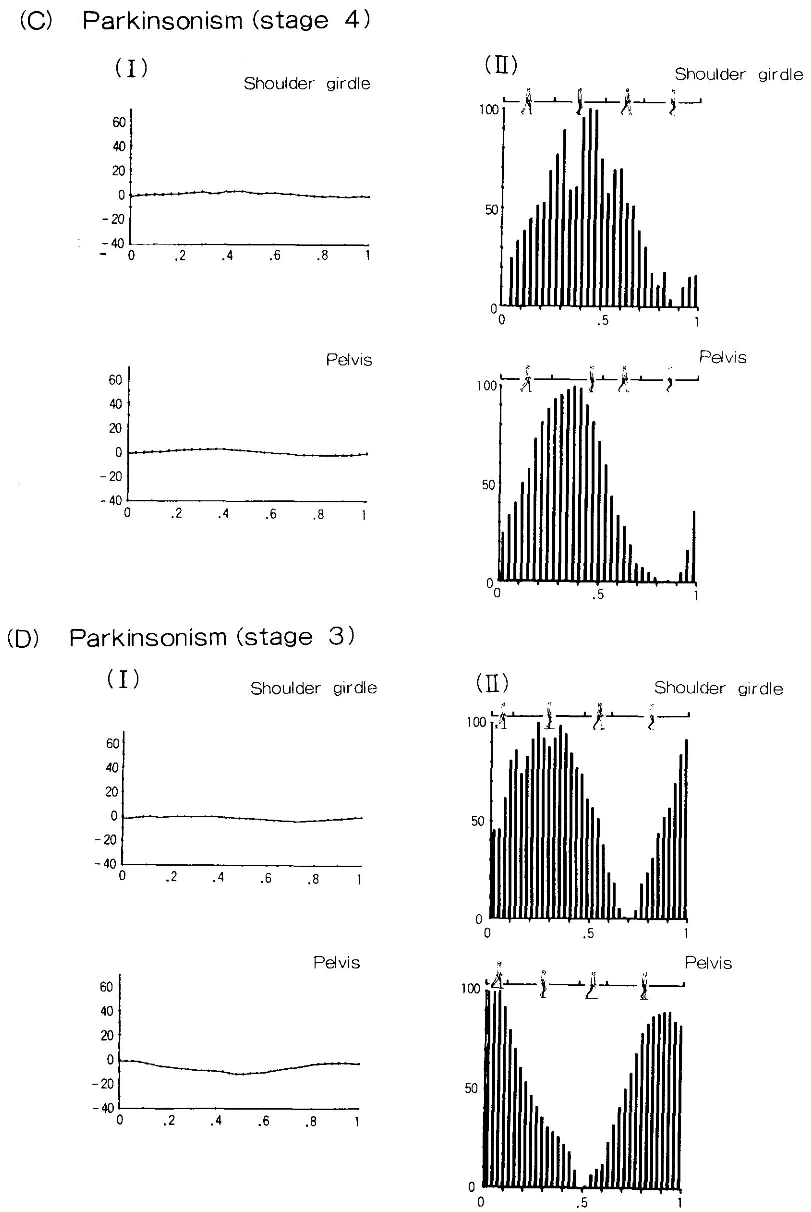

Fig. 9. (I) Mean patterns of the shoulder girdle and pelvis in patients with parkinsonism at YAHR's Stage 4 (C-I) and Stage 3 (D-I).
(II) Normalized patterns of the shoulder girdle and pelvis in patients with parkinsonism at YHAR's Stage 4 (C-II) and Stage 3 (D-II).

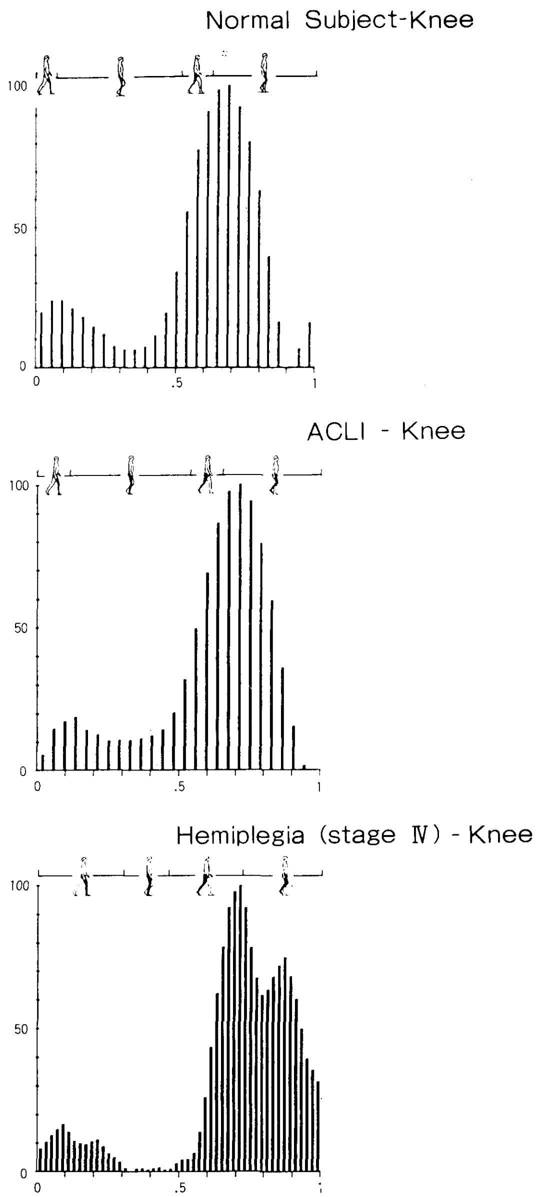

Fig. 10. Normalized patterns of the knee joint in a normal subject, the patient with ACLI and the hemiplegic patient at BRUNNSTROM's Stage Ⅳ.
The cadences in a normal subject, the patient with ACLI and the hemiplegic patient were 104.0 steps/min., 110.8 steps/min. and 57.6 steps/min. respectively.

SUBJECTS	NUMBER OF BARS	CADENCE (steps/min.)
NORMAL ADULT	27	104.0
OSTEOARTHRITIS		
THE HIP JOINT	26	110.8
THE KNEE JOINT	28	102.9
THE ANKLE JOINT	34	84.7
ANTERIOR CRUCIATE LIGAMENT INSUFFICIENCY	26	110.8
HEMIPLEGIA		
STAGE Ⅳ	50	57.6
STAGE Ⅵ	36	80.0
PARKINSONISM		
STAGE 3	36	80.0
STAGE 4	31	92.9
ANKYLOSING SPONDYLITIS	35	82.3
LUMBAR DISC HERNIATION	34	84.7

Table 2. The number of bars of one walking cycle and the cadence in a normal subject and ten patients.

Figure 10. The interval between bars in the hemiplegic patient was narrower when compared with those in a normal subject and the patient with ACLI.

DISCUSSION

Ⅰ. Validity of Method

1. Stick-picture

This method using a stick-picture camera facilitated the measurement of the angles of the extremity joints and body rotation, using long running film, as compared with the previous method which used standing film.

2. Mean Pattern

The mean angular changes obtained in this study were in accordance with those obtained by MURRAY *et al.*[7)8)]

The average maximum rotation of the shoulder girdle and pelvis were much smaller than those of other joints. Therefore, in the shoulder girdle and pelvis it was difficult to evaluate their transverse rotation only by the mean patterns. Furthermore, the cycle time and cadence could not be represented in the mean patterns. For these reasons, the normalization of angular changes was performed.

3. Normalized Pattern

The normalized pattern can be immediately illustrated as a constant length of the X-axis and Y-axis when the data are fed into a computer.

The characteristic features of the normalized pattern were considered from two standpoints; the X-axis and Y-axis. In the Y-axis, it was easy to recognize the rotations of the joints of which angular changes were very small. Therefore, normal or abnormal locomotion could be easily recognized at a glance, using a pattern recognition technique. In the X-axis, a prolongation or a shortening of the cycle time could be easily recognized at a glance by the density of bars during one walking cycle. In addition to this, the cycle time and cadence could be easily calculated with the number of bars during one walking cycle.

II. Transverse Rotation of the Shoulder Girdle and Pelvis

MURRAY[8] reported that smooth forward translation of the trunk is one of three qualities which characterize normal locomotion.

DUCROQUET[2] emphasized an important role of transverse rotation of the shoulder girdle and pelvis in the normal adult walk.

INMAN and SAUNDERS *et al.*[14] reported that pelvic rotation is one of the major determinants of locomotion which serves to lessen the amplitude of the vertical movement of the center of gravity of the body during each step.

In the previous angle-time diagram (the mean patterns), it was difficult to recognize the transverse rotation of the shoulder girdle and pelvis because their mean angular changes remained relatively level throughout one walking cycle, as shown in Figure (7 (I), 8 (A, B-I), 9 (C, D-I)).

In the normalized patterns the patterns of angular changes were scaled up so that the characteristics of the transverse rotation of the shoulder girdle and pelvis could be easily recognized at a glance.

In a normal subject, the shoulder girdle and pelvis rotated simultaneously in opposite clockwise and counterclockwise directions, producing coiling and recoiling types of movement of the trunk during each walking cycle (Figure 7 (II)).

In the BRUNNSTROM's classification[1] of hemiplegia, Stage IV is more severe than Stage VI. The shoulder girdle and pelvis in the patient at Stage VI showed a more similar pattern to a normal subject than in the patient at Stage IV (Figure 8 (A, B-II)).

In the YAHR's classification[5] of parkinsonism, Stage 4 is more severe than Stage 3. In the same manner, the shoulder girdle and pelvis in the patient at Stage 3 showed a more similar pattern to a normal subject than in the patient at Stage 4 (Figure 9 (C, D-II)).

From the preceding description, it may be considered that the normalized patterns are very important to indicate the extent of disability and to show the recovery stages of hemiplegia and parkinsonism.

Ⅲ. Cycle Time and Cadence

It could be seen in Figure 10 that the interval between bars in the hemiplegic patient was narrower compared with those in a normal subject and the patient with ACLI. This means there is a prolongation of the cycle time, because the X-axis is printed in constant length. The cycle time and cadence could be easily calculated with the number of bars during one walking cycle.

Ⅳ. Characteristics of the Normalized Angle-Time Diagram

The normalized angle-time diagram of walking described above has following characteristics:

1) The type of angular changes is easily recognized at a glance even in the motion with very small amplitude.

2) The velocity of walking is also easily recognized at a glance and the cycle time and cadence are easily calculated.

Therefore, this diagram is thought to be very useful for the analysis of pathologic gait.

SUMMARY

1) Five normal and ten pathologic gaits were analyzed using the normalized angle-time diagram.

2) Normal or abnormal locomotion could be easily recognized at a glance even in the motion with very small amplitude.

3)The velocity of walking could be also easily recognized at a glance and the cycle time and cadence could be easily calculated.

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