MODEL ANALYZING METHOD FOR GAIT EVALUATION

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1. Relationship between Model Analysis and Gait Evaluation

Gait evaluation is generally performed by some peculiarity or indices based on measured data of a practical walking (Fig. 1). Contrary to this, model analysis is done by some calculated or estimated data of an assuming condition. The model analyzing method was usually distinguished from the traditional gait analysis because of the difficulty and the delay in a clinical application.

\[ \text{measurement} \rightarrow \text{subject} \rightarrow \text{model} \]

\[ \text{wave processing} \rightarrow \text{evaluation} \rightarrow \text{calculation} \]

Fig. 1 Different approaches of gait analysis

The concept of modeling, however, is rather easy and applying to the traditional gait analysis (Fig. 2). Namely the choice of parameters and conditions of measurement are done by a link image of the object's exercise. A pathological signs and noise signals have to be distinguished by some criteria based on a prediction of an abnormal motion. The mutual relation among the measured data must be understood by a hypothetical mechanism of the exercise.

These clues will be called as a subconscious model. In case of the model analyzing method, a model is represented by equations and operated numerically by a computer. Therefore, both approaches in Fig. 1 are fundamentally same as regarding to the use of a model conception.

\[ \text{subject} \rightarrow \text{measurement} \rightarrow \text{wave processing} \rightarrow \text{evaluation} \]

\[ \text{model of exercise} \rightarrow \text{model for discrimination} \rightarrow \text{model for understanding} \]

Fig. 2 Subconscious model

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2. Model Analysis and Simulation

Body exercise is achieved by many internal structures and functions including the neural and the circulator systems. The model analysis for the gait evaluation is applied usually to know the mechanical functions and the affections of musculo-skeletal system. Because these structures and functions can not be observed and measured directly, the analysis is performed by computer simulation methods.

The word of "simulation" means the analyzing method using a simple imitation instead of the object's system. The imitated system is called as a model. One should note that the model does not need to resemble all of the real system. Conversely, it needs to clarify the purpose of the analysis before a model construction.

The purposes of motion analysis are classified as shown in Fig. 3. To know the range of joint motion and the difference of body proportions is rather easy. But to know the internal forces acting on the joint is difficult. Further, it is more difficult to estimate the effect of a morphological changing or clinical treatments to the exercise. The model analyzing method is useful to solve these difficult problems.

![Diagram](image)

**Fig. 3 Components of model analysis**

There are two kinds of mechanical analyzing methods concerning to know the relationship between a exercise and internal forces. One is to estimate a motion from the given internal forces. And the other is to estimate internal forces from the observed motion. The observation of body exercise is generally easy, but the measurement of internal forces is almost impossible in a living man. Accordingly, the former is used to accept in the field of the robotics, and the latter is applied to the clinical purpose. An application of the former method will bring remarkable capability to the decision about a clinical operation and training in future.

The problems concerning to morphological parameters are the body proportions such as a difference of leg length and the muscular arrangements. The former relates to the natural periodic motion of whole body. The latter affects internal forces through the equilibrium of joint moments. These are very
3. General procedure of model analysis

The model analysis is performed commonly by the following procedures.

1) Modeling of concerned exercise.
2) Modeling of concerned body mechanism.
3) Deducing the equations of motion.
4) Examination of the solution.
5) Estimation of parameter values in the equations.
6) Evaluation of the calculated results.
7) Discussion by the calculated results.

The freedom of the exercise must be reduced, or the dynamic activity must be ignored for simplification according to the characteristics of the exercise and the purpose of the analysis. Body segmentation and freedom of the joints are also simplified corresponding with the modeled exercise. It is necessary to simplify the musculo-skeletal system if you want to know the muscle forces during the exercise. The step 3) and 4) are the applications of the knowledge of dynamics of a rigid body and the numerical calculation. In some cases, special techniques become necessary to optimize a solution or to speed up the calculation. The parameter values included in the equations of motion are given by referring to the experimental data. The experimental data are also useful to evaluate the calculated results.

These procedures must be repeated until the calculated results have good reliability. The development of a model needs not only the anatomical, kinesiological, dynamic, and computer programing knowledges, but also many efforts and terms. By the above mentioned complicated reason, model analysis had not been applied in the clinical evaluation.

Recently, however, we can easily use the method because rather practical models have been proposed, and the cost of an apparatus for the calculation has extremely decreases. Regardless of the practice of simulation, the most important contribution of model analysis to gait evaluation is that the concept can change the subconscious model in Fig.2 to more clear mechanism, and that the concept can lead to more essential understanding of the measured data.

4. Practical method on modeling

A human body can be divided into several segments depending on the anatomical structures and the purpose of the analysis. Each divided segment can be regarded as a rigid body if we can neglect the deformation of the soft tissues accompanying with exercise. Consequently, the morphological characteristics of body can be expressed by the dynamic properties of rigid body such as a mass, length, the position of the center of gravity, and the moment of inertia, and the anatomical properties of
musculo-skeletal system such as a joint resistance, position of muscle insertion, and the direction of muscle force. The characteristics of rigid body are obtained from the product of density and volume of each segment. The volume can be calculated from the integration of thin parts which are approximated ellipse sections (Fig.4). The standard values represented by the function of body weight and stature are proposed for simpler estimation.

The elastic resistance of each limb joint increases exponentially close to the movable limit. The relation between the torque of resistance and the joint angle can be measured with a tension meter and a goniometer (Fig.5). The value of damping coefficient of joint is obtained from a damped curve of the natural swing of a segment but is negligibly small comparing to the elastic torque.

The attached points and the directions of muscles and ligaments are estimated from an anatomical specimen or atlas. But this work is very hard because practically the attached point spreads practically into wide range, the fibers of soft tissues points to three dimensional directions, many soft tissues relate in one motion, and each tissue achieves various functions. Therefore, the determination of those musculo-skeletal parameters must be done empirically.

5. Estimation method of internal forces

Muscle forces are changed to joint moments by the link mechanisms of the bones and joints. If we know the joint moments during exercise and the musculo-skeletal arrangement, with converse way, we can obtain the muscle forces which are hard to measure directly.

Let us consider the knee joint moment as an operative example (Fig.6). The shank and foot are combined with each other as a rigid link. The knee joint rotates in a sagittal plane like
pin joint. And the following symbols are used: ground reaction force(R), moment arm of the ground reaction force against the center of knee joint(a), shank and foot weight(W), distance from the center of gravity to the center of knee joint(c), moment of inertia about the knee joint axis(I), joint angle from perpendicular(θ), angular acceleration of θ(θ).

The moment about knee joint(M) is expressed by the moment of inertia, segment weight and reaction force as Eq.(1).

\[ M = I \theta + Wc \sin \theta - Ra \]  

(1)

In Eq.(1), the morphological parameters(I,W,c) and the kinesiological parameters(θ,θ,R) are determined by the actual measurements. Therefore, the knee joint moment(M) is obtained from the measured data.

The joint moments caused by the body weight and external forces must be balanced by the inner moments caused by the muscular and ligamentous forces. For example in Fig.6b, F,r and T denotes a muscular force, moment arm of the muscular force and resistant torque which is the function of relative joint angle(φ) and angular velocity(φ), respectively. The moment equilibrium equation become as follows:

\[ M = Fr + T[φ,φ] \]  

(2)

where F is extensor when M is positive, and the reverse is flexor. Therefore the muscular force(F) is estimated from the anatomical data(r), joint resistance(T) and kinesiological data(φ,φ). The angular velocity and acceleration are obtained by a numerical differentiation.

Figure.7 shows the generalized procedures and necessary models for an estimation of inner forces. Even if the link model became complex, the calculation of joint moment can be easily performed because the differential equations changes to algebraic equations by substituting measured morphological, kinesiological and mechanical data for the equations.
Each joint moment is equal to the sum of the products of all muscle forces acting at the joint and their moment arms. The number of the unknown inner forces which are assumed in the musculo-skeletal model exceeds the number of the equilibrium equations of joint moments. For this reason, some restrictions about muscle activities and an optimization technique are applied practically to the estimation of inner forces. The forces transmitted by joints and the energy expenditure during the exercise are obtained with the calculated muscular and resistive forces.

The reliability of models and calculations can be checked by comparing the calculated results to experimental results such as electro-myogram. They must be improved until they approximate to the living man and until the calculations become reliable. This is the nature of the computer simulation method[1].

Figure 7 shows the calculated results of joint moments and inner forces during normal walking. Assumed link model consists of seven rigid segments (i.e., thighs, shanks, feet, and upper body), each restricted to movement in a sagittal plane. The musculo-skeletal model was constructed to have eight principal muscle groups as shown in Fig. 9. The members of these muscle groups were selected by the function, simultaneity of muscular activity, and concerned the joint numbers. For further simplification, the relative direction of muscle force against the bone was assumed constant during walking.

The decrease of the joint moment and the extensor forces in a hip and a knee during the middle stage of stance phase are caused by the structural supporting due to the erection of the leg. In the case of inclined posture, the extensor forces and the joint loads in the hip and the knee joint become larger than those of the erect walking. Therefore, it is found that the reduction of the joint loads is achieved by the erect and extended walking.

The estimation method of internal forces is useful to decide on an application of the clinical operation and the planning of therapy because the method gives internal forces rather easily, and is based on the data of practical walking. The method may be also applied to the calculation of loads on prosthesis.
Joint moment / Body weight Muscular forces / Body weight Joint force / Body weight

Fig. 8 Joint moments and inner forces in normal gait (10 persons).

Fig. 9 Musculo-skeletal model.

6. Kinesiological measurements for model analysis

6.1 Motion data
The calculation of joint moment is done by using the data of joint angles and external forces. The changing patterns of joint angles in walking are often measured in clinical gait analysis.
But in this case, the measurement is usually performed about only diseased joint with an electro-goniometer. Contrary to this, the calculation of joint moment needs all joint angles of modeled segments. The joint angles, however, must be obtained from the displacement data of each joint because the accuracy of displacement is decreases if the calculation is traced backward from the measured angle, and also because the multiple measurement of joint angles is practically difficult. Consequently, if you want to develop a model analyzing method in the near future, you might select a good apparatus for measurement of spatial displacements.

Optical apparatuses require rather large space, long preparation time, higher cost, and special software in the measurement. For this reason, it seems that the measurement by the optical apparatus does not suit to a daily clinical experience. But the apparatus has expansive ability to model analysis.

Figure 10 shows an example of the measurement by a PSD (Position Sensitive Diode) camera system. The targets with infrared LED (Light Emitting Diode) were attached on the acromion, stylion, iliocristale, trochanterion, merion latellare, supratarsale fibulare, and metatarsale fibulare. The preparation of this measurement was done within five minutes. The distance from walk way to the camera was 4.5 m using 35 mm lens. Therefore, the measurement of this condition will not disturb so much a daily clinical works.

The measurement of iliocristale and trochanterion points becomes impossible by the interference of a swinging arm. The short lack in a continuous data can be estimated by an interpolation method. The opposite side data were obtained by means of shifting the measured data in half a period assuming a symmetrical gait. The torso displacements were determined by averaging the both side data. But the joint moment of one side leg can calculate only by using measured data.

It is better to start from a simple and easy application in which the measured data itself are useful to a clinical

![Diagram](image)

Fig. 10 Example of a Kinesiological measurement.
evaluation, and to progress to the next step after sufficient understanding about the system. If you want to get a complete system at the start, you should waste your time and labor, and the system will become finally troublesome and useless.

6.2 Mechanical data

Necessary mechanical data are the magnitudes, directions and application points of all external forces. The force platform which has become a standard apparatus of gait analysis satisfy the requirements, and the measured data can be applied directly into model analysis. But the coordinates of the application points of external forces must coincide more exactly with the coordinates of the spatial points of segmental motions than those in traditional gait analysis. The error of the origins of both coordinates affects directly the error of the calculation of joint moment. In order to achieve the coincides of both coordinates, you need only measurement of the target points and application points of force by a calibration weight with LEDs before the practical measurements. Such a little care brings the application of the measured data to the next step.

6.3 Physiological data

The physiological data such as electro-myographic data and the energy consumption do not need to calculate the joint moment. These are useful, however, to evaluate the results of model analysis. Especially the electro-myographic data become the fundamental data for the development of an estimation procedure of muscle forces, because the muscular activities in pathological gait may differ from those in normal gait.

Some filtering process is necessary before applying the electro-myogram and kinesiological data simultaneously to a computer. Because electro-myographic data have high frequency and kinesiological data have low frequency, consequently, the determination of sampling rate arises. The estimated muscular activities are evaluated by the envelope of electro-myograms which are obtained by an analog filtering. It may be difficult to collect the physiological data in a daily clinical experiments for the reason of time-consuming preparation. Therefore, a special measurement must be planed to collect the records of typical pathological gaits.

6.4 Construction of software for model analysis

Figure.11 shows an example of a software flow which intends to expand into a model analysis. The whole aspect of an apparatus and a programing depends on the selection of the measurement method of the joint motion. In case that the measurement depends closely on a computer, the system lose flexibility but decreases user's duty.

It is more efficient and convenient to use each measurement apparatus simultaneously or independently. Therefore, the software for measurement and recording must be also made in order to do so. Personal data such as the name of patient, age, sex, etc. are given in the first input part. These data are utilized to the classification and reference of patients.

The analyzing routine are better to be divided into each independent program from the measurement routine for the reason of expansibility and maintainability of the total program. Each
application program which are separated by the function of apparatus or analysis are performed through common data file. The personal data concerning to the application analysis such as the rigid properties of segments are given in this routine. According to the independent construction, each program become redundant, but the improvements and additions of new programs become easy because the interference among programs is free. A continuous processing for simple apportion from a measurement to final output is given by the selection of a combined course menus.

By this construction, a minimum measurement and evaluation are performed, and to develop the analysis step by step according to the accumulation of experiences and data. The flexibility is important not only to develop the program by yourself but also to order it to some company. Practically, we will encounter many unexpected troubles in the measurements and processing, and will arise higher expectation after solving those problems. Accordingly, we suggest to construct the system by having a growing plan from a independent measurement in the first step, the synchronous measurements in the second step, and so on, to a model analysis.

7. Role of model analysis in gait evaluation

The principal purpose of gait evaluation will be divided into the three stages in Table 1. The first of them is the objective confirmation of the effect of a training and treatment. This can
be achieved by the comparison of the different data of the same subject. The system for this purpose is necessary to record objectively the characteristics of a motion, and to know the changing corresponding to recuperation in the records. A simple method for this purpose is the measurement of floor reaction forces and comparison of the wave patterns. To know the degree of recuperation, however, the next stage of evaluation must be done.

The second evaluation is the judgment of a degree of disease. In this purpose, a standardized and synthesized evaluation is necessary for the comparison of different subjects. Some characteristics which will relate to the degree of disease are selected based on the data of the first stage of evaluation. The selected characteristics are represented some indices. Each index is standardized by the average and the standard deviation. The total score is obtained by adding up the standardized indices after checking of each independent. The scaling of the score must be done on comparing with clinical judgments. Therefore, this evaluation needs a large number of measured data and clinical judgments, and the knowledge about the statistical processing.

The purpose of the third evaluation is to determine a goal of recuperation and training. The evaluation must be done by a standard conditions of each disease and a prediction of a patient's condition. And the evaluation is expected to inform rather partial condition.

Table 1. Purpose of gait evaluation and engineering task

<table>
<thead>
<tr>
<th>Clinical purpose</th>
<th>Engineering task</th>
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<tbody>
<tr>
<td>Confirmation of effect</td>
<td>Objection</td>
</tr>
<tr>
<td>Judgment of degree</td>
<td>Scaling</td>
</tr>
<tr>
<td>Determination of goal</td>
<td>Prediction</td>
</tr>
</tbody>
</table>

The prediction concerning to the limit of recuperation, the decision of an application of treatment, and the efficiency of a rehabilitation program may be made by the grasping the accurate condition of a disease and by the analogy from a past resemble diseases. However, it is practically very difficult to predict them even in sufficient experiences.

Contrary to this, the model analyzing method can estimate definitively the individual gait pattern from the expected condition, or the necessary condition to active a expected gait pattern. Furthermore, the estimation does not need so many pathological data, and is useful to propose a definite plan because it is based on the physical relation between the musculo-skeletal system and exercise.

8. Model analyzing method for estimation of gait pattern

8.1 Estimation method

It is natural to think that daily exercise like a locomotion
is carried out with the motion of the least energy consumption. The condition can be achieved when the motion coincides the natural vibration mode in the body proportions. The vibration mode is calculated from a link model like a marionette in Fig.12 which is segmented more actually than the model for estimation of internal forces.

The model consists of 11 links, resembling a human body, i.e., of a head and a neck, a chest, a hip, left and right thighs, shanks and feet, upper arms, and forearms and hands. The knee, elbow and waist joints are assumed having a visco-elastic resistance. Any external forces except gravitational force does not applied. Suppose we make a wooden link model and suspend the top of the head by a thread, the oscillation of legs is propagated to upper parts as a chain reaction. Consequently, we will observe a whole body motion which may be similar to gait pattern.

The whole body motion can be calculated by the equations of motion derived with the link model. This method has more advantages than the experimental method by the above physical model, because the method gives a hypothetical conditions easily by changing the model parameters. Furthermore the method is useful to evaluate the influence of a partial changing to the whole motion.

The equations are represented by 12's simultaneous non-linear differential equations of the joint angles and the displacements of the center of gravity. These equations includes the segment parameters as a rigid body and the joint properties. The vibration mode is calculated numerically from adequate initial conditions.

Figure.13 shows the results of calculation about the body proportions of an adult man. You will able to understand that the relative motion of upper and lower limbs, and the movement of the chest and pelvis in the vibration mode agree well with the actual walking pattern[2].
8.2 Influence of aging on gait

In the growth process of man, the body proportions are changed remarkably as well as the development of muscular and neural system. The changing affects into the amplitude of wave components included in the vibration. The fundamental vibration relating to the harmonic motion increases rapidly until three years old. The components of high frequency relating to the unsteady motion are decreased until seven years old. Walking speed is increasing until near fourteen years old. The vibration mode of whole body converges to the adult mode at about sixteen years old when the growing of body proportions also converges. These results almost agree with the experimental results by foot force and electromyogram.

An old man whose body proportions does not change so much walks bending the upper parts of the body a slightly forward. The resulted walking becomes as shown in Fig.14. The walking speed slow down, and the smoothness and reappearance of the motion are disappeared. These characteristics of walking are agree with the practical walking of old men. Namely, the changing of the body proportions and posture along with aging is the dominating cause of the forming of gait pattern[3].

The calculation method of the natural vibration mode is also applied to the evaluation of a prosthesis and orthosis design. The applications of these artificial things to the body change partially the characteristics of the joint and the segment. Consequently, the natural vibration mode converges another

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Fig.13 The natural vibration mode in adult man.

Time interval: 0.2 sec

Fig.14 The natural vibration mode at inclined posture.

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stable pattern which represents the affection to the gait. We can expect a good result of the application if the changed pattern is a better one. In case that asymmetrical changing is caused by the application of prosthesis or orthosis, rotation of upper torso and swing of upper arms increases in order to cancel the unbalanced moments. Therefore the effect of these artificial things must be evaluated not only about the leg motion but also based on the whole body motion.

9. Possibility of model analysis

The model analyzing methods are classified under the purpose and necessary data in Table 2. The estimation method of inner forces as mentioned in section 5 calculates the muscular and joint forces based on the measured exercise and morphological characteristics of a patient. And the method in section 8 estimates the motion corresponding to the morphological characteristics under the action of gravitational force.

<table>
<thead>
<tr>
<th>Purpose of analysis</th>
<th>Morphological characteristics</th>
<th>External forces</th>
<th>Motion of segments</th>
<th>Inner forces</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimation of inner forces</td>
<td>data</td>
<td>data</td>
<td>data</td>
<td>results</td>
</tr>
<tr>
<td>Estimation of motion</td>
<td>data</td>
<td>data</td>
<td>results</td>
<td>data</td>
</tr>
<tr>
<td>Estimation of stabilizing</td>
<td>data</td>
<td>data</td>
<td>results</td>
<td>results</td>
</tr>
<tr>
<td>Synthesize of exercise</td>
<td>data</td>
<td>results</td>
<td>results</td>
<td>results</td>
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</table>

The third method of model analysis is applied to the analysis of the joint instability and ligament load. In these problems, it is necessary to calculate the equilibrium of external and internal forces. The joint mechanisms in the first and second methods are assumed simply as a pin joint. But the joint bones are usually combined with each other by soft tissues such as the ligaments, and able to move relatively on the joint surface. The amplitude of the slip is determined by the equilibrium of all forces applying there. But the inner forces are changed by the slip because of the changing of moment arm. Therefore in this case, a convergent calculation is necessary to get a balanced condition from a initial position[4].

By means of this method, the effect of an operation such as the ligament cutting or transfer can be easily estimated. It is possible in the future to extend a computer aided system for clinical evaluation to the selection and development of a joint surgery.

The forth method of model analysis is to estimate the exercise like an upper arm motion or jumping motion which is exerted dominantly by muscular forces. In this case, complex
differential equations of the rigid link model and the musculo-skeletal model must be solved by using a criteria and restrictions relating to muscular activities. The criteria is expressed usually by the formulation of minimum energy in mechanical problems. But the energy must be represented by the physiological parameters based on a musculo-skeletal characteristics[5].

The method can be expected many clinical applications because of the advantage of the computer simulation which permit the impossible experiences in the real system. In order to enter the new stage of the clinical evaluation, however, we must devote ourselves to develop the model analyzing method.

References

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