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Computerized analysis and modelling of patients with deformities of lower limbs

JOLANTA PAUK*

Białystok Technical University, Białystok, Poland.

The purpose of this paper was to model the human gait of typical subjects and patients with such deformities of lower limbs as: spastic diplegia cerebral palsy and spina bifida occulta. Model coefficients will lead to the development of a better computer system to support clinical decision-making in human gait in terms of assessment, diagnosis, and classificatio,mnn. Human gait was evaluated by using Motion Analysis System in the Syncrude Center for Motion and Balance in Edmonton. Kinetics data were used for the mathematical modelling based on regression function. The difference between the model coefficients of the patients with the deformities of lower limbs and typical subjects were analysed. There is shown that the model coefficients are different in each group. The modelling can help to define gait pathology and treatment for a large number of patients.

Key words: *regression function, modelling, human movement, diagnosis, cerebral palsy, spina bifida*

1. Introduction

Human walking is an example of a well-learned fundamental movement pattern that in normal situations is performed with a great deal of coefficiency and consistency. Gait analysis and modelling have long been used as a research tool to develop the complete understanding of the mechanics control of human movement. A standard physical examination cannot provide any complete description of pathology of abnormal human gait, while gait analysis and modelling can. Computerized gait analysis is often performed to enhance clinical decision-making, and due to a mathematical modelling can be an important tool for quantifying normal and pathological patterns of locomotion. With this information, more informed decision-making about treatment to improve gait function is possible. Many researchers take an analytical approach to the synthesis of motion, using trial and error, dynamic optimization, or other control schemes to develop the proper force time histories necessary to drive the motion. ONYSHKO and WINTER presented an important model of locomotion in 1980 [1]. In their article, the issue of responsible modelling was stressed in regard to pure synthesis (forward dynamics). One of the few dynamic models of the knee joint was presented in 1988 [2]. The approach involved the development of a 3D model that was later reduced to a 2D model for the analysis and simulation of motion. One of the first studies in the synthesis of locomotion using modern computers and optimal programming was presented by CHOW and JACOBSON [3]. This model incorporated the musculoskeletal system in detail, including the nature of neurophysiology, human control, and stability strategies. HATZE and coworkers have been instrumental in the area of dynamic synthesis of human motion. They proposed the model of a single leg in which five muscle groups were used in a time-optimal problem [4], [5]. In a later study, these methods were extended to the entire human body. HEMAMI and STOKES presented an overview of the

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* Corresponding author: Jolanta Pauk, Białystok Technical University, Wiejska 45C, 15-351 Białystok, Poland. E-mail: jpauk@pb.edu.pl

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types of control systems that might be used for the simulation of human locomotion [6]. MEGLAN presented a global approach to the analysis of human motion in his Ph.D. dissertation [7]. He developed a comprehensive method for the understanding of dynamic coupling effects in human movement. The models of gait based on a single concentrated mass were presented by SIEGLER and SELIKTAR [8]. YAMAGUCHI has contributed to the area of muscle modelling and dynamic synthesis of gait in several works. He investigated the prospects of restoring natural gait to patients with paraplegia using functional neuromuscular stimulation (FNS) [9]. Yamaguchi increased the complexity of a human model to address many of the unanswered questions in the study of locomotion, particularly with respect to the analysis and treatment of pathological gait. YEADON presented an application of dynamic synthesis to the motion of the human body in athletic aerial maneuvers. A comprehensive methodology was developed for the determination of kinematics [10], the modelling of a specific subject using body measurements, the determination of the angular momentum of the entire body in flight, and the simulation of the motion using dynamic modelling. ZAJAC and GORDON presented a comprehensive paper on the dynamics of human motion, in which the complexity of dynamic coupling effects was the focus of interest [11].

The goal of this work was to provide a model and associated data capable of being used for clinical decision-making for the lower limbs.

2. Material and methods

Functional evaluation was carried out on 30 typical subjects (the average age of 23 yr.), 40 patients with spastic diplegia cerebral palsy (the average age of 20 yr.), and 45 patients with spina bifida occulta (the average age of 18 yr.). Patients with spastic diplegia cerebral palsy characterized of spasticity in the muscles of the lower extremities of the human body, usually those of the legs, hips and pelvis. They had serious functional difficulties in sitting, standing and walking. Patients with spina bifida occulta suffered from the weakness in their legs, foot deformity, and had problems with gait (walking). They also felt back pain. Patients were recruited into Glenrose Rehabilitation Hospital (laboratory of the Syncrude Centre for Motion & Balance) in Edmonton. In the motion lab, Instrumented Gait Analysis is used to provide quantitative data on a subject's joint motion, net joint rotatary forces and muscle activation. A multidisciplinary team consisting of engineering, physical therapy, kinesiology, physiatry and orthopaedic surgery staff used these data both to determine the suitable customized treatment options and to assess the outcome following treatment. Equipment in the motion analysis laboratory consists of eight cameras for recording body/joint motions and three AMTI force plates, installed in a raised floor, and ten-channel Motion Lab Systems surface EMG system for recording muscle activity. The subjects were analyzed while walking barefoot along a straight pathway 10 m long. The location of the markers on each subject was the following: two on the Posterior Superior Iliac Spines, one on the Sacrum Bone, two on the Lateral Femoral Condyles, two on the Lateral Malleoli, and one on the Wrist. Pre-processing of raw data involved a tracking procedure, three-dimensional reconstruction of the marker's coordinates, correction for optoelectronic distortion, and filtering. The frequency of acquisition was set at 60 Hz. All the variables were time-normalized taking the whole stride duration as 100%.

2.1. The regression model of human gait

Model studies have been performed to characterize the human gait of typical subjects and patients with the deformities of lower limbs. The approach to human gait is based on regression function. The kinetic parameters (especially power developed by muscle joints) applied to construct the mathematical model were determined in the hip joint, knee joint, and ankle joint separately under similar conditions used for the stance and the swing phase. The mechanical power associated with joint rotation was computed from the combination of the joint moment and the joint angular velocity (the rotational velocity of one segment relative to another) [12]. The formula for power joint is facilitated through:

$$P_i = \vec{M}_i \cdot \vec{\omega}_i , \tag{1}$$

where:

P_i – the joint power,

$\vec{M}_i$ – the joint moment,

$\vec{\omega}_i$ – the angular velocity.

The model proposed by the author is based on instantaneous power developed by muscle joints of lower limbs in the stance and the swing phases. The regression model of human gait is determined as follows:

$$\hat{Y}_n = \underline{u}_n \cdot \underline{a}, \quad n = 1, 2, ..., N, \tag{2}$$

where:

$\hat{Y}_n$ – the model's output (power developed by muscle joints in the n-th instant),

$\underline{u}_n$ – the model's input (power developed by muscle joints in the n instants before),

$\underline{a}$ – the unknown vector of model coefficients,

N – the sample size.

The vector $\underline{a}$ is determined by equations (3) and (4):

$$\underline{a} = (\underline{\underline{U}}^T \cdot \underline{\underline{U}})^{-1} \cdot \underline{\underline{U}}^T \cdot \underline{Y}, \tag{3}$$

where:

$\underline{a}$ – the unknown vector of model coefficients,

$\underline{\underline{U}}$ – the matrix of input data,

$\underline{Y}$ – the vector of output data,

$$\underline{a} = [a_1 \quad a_2 \; ... \; a_k]^T, \; k = 1, 2, ..., K, \tag{4}$$

where:

$\underline{a}$ – the unknown vector of model coefficients,

K – the coefficient size.

The regression model presents the relationship between the power developed by muscle joints in the n-th instant and power developed by muscle joints in n instants before. The best results were obtained for approach where the power developed by muscle joints in the n-th instant depends on power developed by muscle joints in three instants before. The vector $\underline{\mathbf{Y}}$ and the matrix $\underline{\underline{\mathbf{U}}}$ can be defined by:

$$\underline{\mathbf{Y}} = \begin{bmatrix} \mathbf{Y}_3 \\ \mathbf{Y}_4 \\ \mathbf{Y}_5 \\ \vdots \\ \mathbf{Y}_B \end{bmatrix}, \quad \underline{\underline{\mathbf{U}}} = \begin{bmatrix} \mathbf{Y}_2 & \mathbf{Y}_1 & \mathbf{Y}_0 \\ \mathbf{Y}_3 & \mathbf{Y}_2 & \mathbf{Y}_1 \\ \mathbf{Y}_4 & \mathbf{Y}_3 & \mathbf{Y}_2 \\ \vdots & \vdots & \vdots \\ \mathbf{Y}_N & \mathbf{Y}_{N-1} & \mathbf{Y}_{N-k} \end{bmatrix}, \tag{5}$$

where:

$\underline{\underline{\mathbf{U}}}$ – the matrix of input data,

$\underline{\mathbf{Y}}$ – the vector of output data.

The representation of real data by the model is shown in the figure.

The representation of real data by the regression model is very accurate. The relative error was around 2%.

3. Results

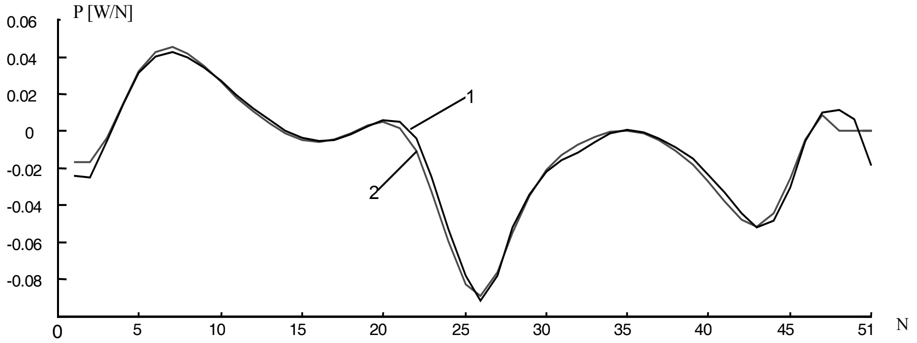
To study the performance of the regression model of human gait, several realizations of a number of process models were generated and the model coefficients were estimated. The regression model coefficients are presented in tables 1–3. They were determined in two phases, i.e. the stance and the swing, for the hip joint, knee joint, and ankle joint. The standard deviation values of the model coefficients for each group are also given in the same tables.

Table 1. Regression model coefficients of typical subjects (±SD)

Joint	Coeff.	Stance phase	Swing phase
Hip	a_1	1.922±0.170	1.761 ± 0.191
	a_2	–1.352±1.067	–0.994±0.291
	a_3	0.303 ± 0.186	0.280 ± 0.050
Knee	a_1	2.033±0.145	1.934±0.147
	a_2	–1.601± 0.298	–1.327± 0.174
	a_3	0.544± 0.223	0.390± 0.203
Ankle	a_1	1.959±0.130	1.211±0.163
	a_2	–1.368±0.140	–0.512±0.160
	a_3	0.488±0.106	–0.039±0.015

a_1, a_2, a_3 – regression model coefficients of human gait.

In the table 2, the regression model coefficients of patients with spastic diplegia cerebral palsy are presented.



Power generated by muscle of knee joint normalised to gravity load of human body for real data (curve 1) and for data obtained from regression model (curve 2) of typical subject;
P – power generated by muscle joints, N – sample size

Table 2. Regression model coefficients of patients with spastic diplegia cerebral palsy (±SD)

Joint	Coeff.	Stance phase	Swing phase
Hip	a_1	1.705 ± 0.108	1.552 ± 0.188
	a_2	−0.855 ± 0.150	−0.549 ± 0.144
	a_3	0.208 ± 0.210	0.154 ± 0.073
Knee	a_1	1.865 ± 0.190	1.588 ± 0.148
	a_2	−0.901± 0.317	−0.859 ± 0.225
	a_3	0.275 ± 0.169	0.208 ± 0.208
Ankle	a_1	1.597 ± 0.134	1.440 ± 0.105
	a_2	−1.012 ± 0.107	−0.361± 0.188
	a_3	0.271 ± 0.113	0.045 ± 0.024

a_1, a_2, a_3 – regression model coefficients of human gait.

The value of the regression model coefficients of patients with spastic diplegia cerebral palsy is lower than those of typical subjects. In table 3, the regression model coefficients of patients with spina bifida occulta are presented. The value of the regression model coefficients of these patients were compared with those of typical subjects. The approach to human gait indicates that the regression model coefficients are much different in each group.

Table 3. Regression model coefficients of patients with spina bifida occulta (±SD)

Joint	Coeff.	Stance phase	Swing phase
Hip	a_1	2.084 ± 0.186	1.743 ± 0.234
	a_2	−1.501 ± 0.176	−1.154 ± 0.168
	a_3	0.386 ± 0.112	0.285± 0.091
Knee	a_1	1.801 ± 0.128	1.909 ± 0.143
	a_2	−1.114 ± 0.157	−1.369 ± 0.185
	a_3	0.241 ± 0.127	0.422 ± 0.249
Ankle	a_1	1.848 ± 0.164	1.145 ± 0.106
	a_2	−1.275 ± 0.168	−0.435 ± 0.186
	a_3	0.299 ± 0.198	0.044 ± 0.021

a_1, a_2, a_3 – regression model coefficients of human gait.

Statistical analysis was performed on the whole population of typical subjects, those with spastic diplegia cerebral palsy and spina bifida occulta. A characterization of the difference was obtained by computing the following parameters: the standard deviation, correlation, variance, and confidence intervals.

4. Discussion

Mathematical modelling is one of the challenging tasks in biomechanics of human gait. The goal of this article was to provide a regression model of human gait and data capable of clinical decision-making for the lower limbs. The solution proposed provides an ability to analyze human gait pattern in easy way and with little cost. The current method demonstrates good agreement with different methods, including the regression function for the prediction of human walking parameters. Jang-Hee Yoo described a method for analyzing and extracting human gait motion by combining statistical methods with image processing. A combination of medical knowledge, image processing and regression analysis was used to label human motion in image sequences [13]. Goulermas presented a novel and extensive investigation of mathematical regression techniques for the prediction of laboratory-type kinematic measurements during human gait [14]. Yamazaki et al. described a statistical approach to modelling and synthesizing human walking motion. In the approach, each motion primitive is modelled statistically from motion capture data using multiple regression hidden semi-Markov model (HSMM) [15]. This study has demonstrated that the current regression model is capable of assessing human gait of typical subjects as well as of patients with spastic diplegia cerebral palsy and spina bifida occulta.

5. Conclusion

Gait laboratories measure joint moments and powers for the hip joint, knee joint, and ankle joint. It is very likely that applying kinetics data, especially power generated by muscle joints, could help to define the level of gait pathology in a large number of patients based on mathematic model coefficients. Hopefully, the accurate computation and interpretation of power joints in combination with the other components of computerized analysis system (neural networks, fuzzy logic) will eventually lead to significant improvements in treatment decision-making in complex gait abnormalities. The considerations introduce an incomplete analysis of spacious problems connected with the classification and improvement of the apparatus of human gait, which is the result of the limited number of the data collected. However, the scientific results obtained lead to the conclusion that the regression model can be applied to determine the properties of human gait, and in consequence to diagnosis of patient's apparatus of movement.

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