2014 5th IEEE RAS & EMBS International Conference on
Biomedical Robotics and Biomechatronics (BioRob)
August 12-15, 2014. São Paulo, Brazil

Comparative Verification into Gait Motion of Healthy Subjects and Trans-Femoral Amputee Based on Singular Value Decomposition*

Y. Hayashi, N. Tsujiuchi, T. Koizumi and Y. Matsuda

Abstract— **In human gait locomotion analysis, which is one useful method for efficient physical rehabilitation to define various quantitative evaluation indices, ground reaction force, joint angle and joint loads are measured during gait. On the other hand, the analysis of the correlation in the recorded joint motion extracts a few simultaneously activating segmental coordination patterns, and the structure of the intersegmental coordination is attracting attention to an expected relationship with a control strategy. However, this procedure has not been applied to trans-femoral prosthetic gait locomotion yet. In this paper, joint angles as kinematic parameters applied on the lower limb of healthy subjects and trans-femoral amputee with the prosthetic limb during their gait locomotion are analyzed by singular value decomposition and mutual comparative verification of them is performed. As a result of the experiments and consideration, the effectiveness of the method using singular value decomposition is validated because it can quantitatively express comprehensive physical phenomena for trans-femoral prosthetic gait.**

I. Introduction

Multiple studies have been performed concerning trans-femoral prosthetic gait with the artificial knee joint as the substitute function of the original knee to control stance phase and swing phase [1, 2]. In this case, it is thought that they must regain moving pattern by gait training using kinematic conditions on the prosthetic limb as quantitative evaluation indices to refine rehabilitation program [3]-[9].

However, constitutive principle as mathematical science concerning gait locomotion of trans-femoral amputee to be able to be those indices has not been validated and clarified yet. Hence, human gait locomotion including trans-femoral prosthetic gait must quantitatively be evaluated by the indices based on principles.

The recent research has shed the induced hypothesis that human gait locomotion is controlled by combining intersegmental coordination patterns called motion modes [10]-[13].

*Research supported by Grant-in-Aid for Scientific Research (B) (25289053), Japan Society for the Promotion of Science.

Y. Hayashi is with the Department of Mechanical Engineering, Tokyo Metropolitan University, 1-1 Minami-Ohsawa, Hachioji-City, Tokyo, 192-0397, Japan (corresponding author to provide phone: +81-42-677-1111; fax: +81-42-677-2701; e-mail: hayashiy@tmu.ac.jp).

N. Tsujiuchi is with the Department of Mechanical Engineering, Doshisha University, 1-3 Miyakodani, Tatara, Kyotanabe-City, Kyoto, 610-0321, Japan (e-mail: ntsujiuc@mail.doshisha.ac.jp).

T. Koizumi is with the Department of Mechanical Engineering, Doshisha University, 1-3 Miyakodani, Tatara, Kyotanabe-City, Kyoto, 610-0321, Japan (e-mail: tkoizumi@mail.doshisha.ac.jp).

Y. Matsuda is with the Kawamura Gishi Co., LTD, 1-12-1 Goryo, Daitou-City, Osaka, 574-0064, Japan (e-mail: matsuda@kawamura-gishi.co.jp).

Therefore, in this paper, joint angle of the lower limb in gait locomotion of healthy subjects and trans-femoral amputee is focused and motion mode is extracted as intersegmental coordination pattern by applying the evaluation method based on singular value decomposition. Furthermore, quantitative evaluation based on comparative verification of analytical results is aimed. Concretely, conventional three-dimensional motion analysis system is used to measurement and analysis of gait locomotion. Moreover, each motion mode is extracted when one gait cycle is divided into four phases as two double support phases and single support phase in the stance phase and the swing phase. Trajectory of gravity point in gait locomotion of each subject is also calculated.

Finally, differences of gait locomotion between healthy subjects and trans-femoral amputee are considered as a comparison and the effectiveness of quantitative evaluation is validated.

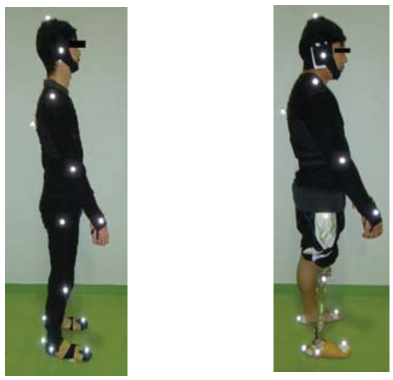
II. Experimental Method

In this paper, four young healthy subjects consisting of three males and one female and one male unilateral trans-femoral amputee with the prosthetic limb participate. Trans-femoral amputee has worn the trans-femoral prosthesis of normal socket-type for at least 30 years. The total mass includes body mass plus the mass of the prosthetic limb. The experiments take place in Science City Campus at Doshisha University, Kyoto, Japan. Human research ethical approval is received from Doshisha University and written consent is obtained from the subjects.

At first, in gait experiment, the subjects perform straight-line level walking when three-dimensional motion analysis system consisting of 10 high-speed digital cameras using infrared ray Eagle (made by Motion Analysis Co., LTD, California, USA) and two force plates OR6-7 (508 [mm] × 464 [mm]; made by AMTI Co., LTD, Massachusetts, USA) is used for biomechanical gait motion analysis. About 20 [min] of practice is performed before the experiments to evidence this confidence.

In addition, three-dimensional position coordinates on the body of the subjects are measured during gait locomotion by a total of 20 infrared reflective markers as shown in Fig. 1. In trans-femoral amputee, positions of markers on the prosthetic limb are similar to positions of markers on the sound limb. Data from the cameras are obtained at sampling frequencies of 200 [Hz]. Three-dimensional position coordinates are measured for at least ten steps when the subjects walk at a self-selected speed.

Here, anatomical antero-posterior direction is equivalent to x-axis (anterior is positive), left-right medio-lateral direction is equivalent to y-axis (left medial is positive) and vertical axis is equivalent to z-axis (upper is positive) as shown in Fig. 2, respectively.



(a) Healthy subject (b) Trans-femoral amputee with the prosthetic limb

Figure 1. Positions of infrared reflective markers.

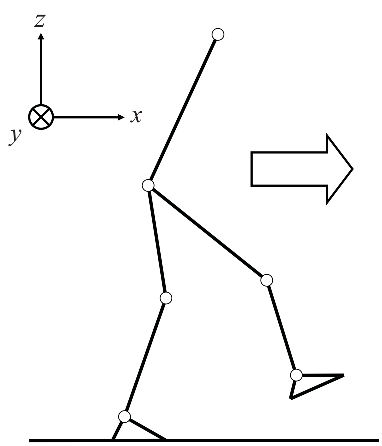


Figure 2. Definition of three-dimensional position coordinate axes.

III. DATA ANALYSIS METHOD

A. Gait Cycle and Calculation of Joint Angle Data

In gait experiment, one gait cycle is defined as the time between ground of right heel and next ground of right heel and is divided into four phases as two double support phases and single support phase in the stance phase and the swing phase. Hereinafter, first phase and third phase are double support phases, second phase is right single support phase and fourth phase is left support phase. Additionally, in respect of kinematic data, rigid link model as shown in Fig. 3 is developed by time-series data of three-dimensional position coordinates of infrared reflective markers on each joint and each joint angle is obtained as absolute angle by them. $\theta_{hip}(t)$, $\theta_{knee}(t)$, $\theta_{ankle}(t)$, $\theta_{foot}(t)$ are time-series data of each right-left joint angle corresponds to hip, knee, ankle and foot, respectively. Moreover, one gait cycle of the obtained joint angle data is focused and the numbers of data points in one gait cycle and each phase are standardized at 700 and 300 by cubic spline interpolation. Time-series data of mean joint angles are also calculated.

B. Singular Value Decomposition of Joint Angle Data

In this paper, a specific evaluation method based on the principle of singular value decomposition proposed by Tsuchiya, Funato and Aoi [11]-[13] is used for quantitatively evaluating intersegmental coordination about each joint of the human lower limb as follows. By writing the time series data of the angles of each joint as a column, the whole movement can be expressed in terms of the matrix. Then, each specific quantitative evaluation index is calculated by using the following formula.

$$R(\theta,t)=\begin{bmatrix} \theta_1(t_1) & \theta_2(t_1) & \cdots & \theta_8(t_1) \\ \theta_1(t_2) & \theta_2(t_2) & \cdots & \theta_8(t_2) \\ \vdots & \vdots & \ddots & \vdots \end{bmatrix} \tag{1}$$

where t is time. An observation matrix is defined as the quantitative evaluation index of the matrix $R(\theta,t)$ that has m number of rows and n number of columns. Moreover, $\theta_j(t_i)(i=1,\ldots,m=700$ or $300,\ j=1,\ldots,n=8)$.

Next, if singular value decomposition is performed on $R(\theta,t)$ and the equation is arranged, $R(\theta,t)$ is expressed as below.

$$R(\theta,t)=R_0+\sum_{i=1}^{8}\lambda_i\ v_i(t)z_i^T(\theta) \tag{2}$$

where $v_i(t)$, $z_i(\theta)$ are eigenvectors of $R(\theta,t)\ R(\theta,t)^T$, $R(\theta,t)^T\ R(\theta,t)$, R_0 is mean posture of $R(\theta,t)$, λ_i is a singular value defined as the contribution ratio of each orthonormal base vector called motion mode that means human motion pattern, $v_i(t)$ is the time variation pattern of motion mode called temporal coordination, and $z_i(\theta)$ is the coordination pattern of motion mode called spatial coordination. Each component is serialized by depending on the magnitude of λ_i value, and its contributing rate γ_i is calculated by using the following equation.

$$\gamma_i=\frac{\lambda_i^2}{\sum_{i=1}^{8}\lambda_i^2} \tag{3}$$

C. Trajectory of Gravity Point

Trajectories of gravity point in gait locomotion of each subject are calculated by using whole position coordinates data and ratio of mass and center of gravity of each body segment. Here, each segment is as shown in Fig. 4. At first, position coordinates of each body segment is calculated as ratio of distance between proximal position and distal position shown in Fig. 5 by using the following formula.

$$x_{cq}=x_{proximal}+R_{proximal}(x_{distal}-x_{proximal}) \tag{4}$$

$$y_{cq}=y_{proximal}+R_{proximal}(y_{distal}-y_{proximal}) \tag{5}$$

where $x_{proximal}, y_{proximal}$ and x_{distal}, y_{distal} are proximal and distal position coordinates, $R_{proximal}, R_{distal}$ are ratios from proximal and distal position coordinates to position coordinates of gravity point on the whole body. Position coordinates of gravity point on the whole body are calculated as weighed mean values of all body segments by using the following formula.

$$x_{total} = \sum_{s=1}^{L} P_s\, x_{cqs} \tag{6}$$

$$y_{total} = \sum_{s=1}^{L} P_s\, y_{cqs} \tag{7}$$

where x_{total}, y_{total} are position coordinates of gravity point on the whole body, x_{cqs}, y_{cqs} are position coordinates of each body segment, P_s is ratio of mass of each body segment, S is the number of each body segment and L is total number of body segments.

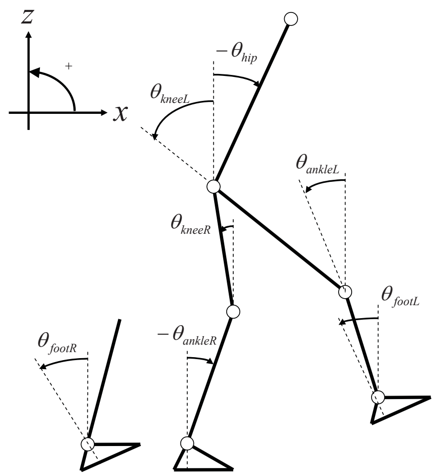


Figure 3. Definition of absolute angle.

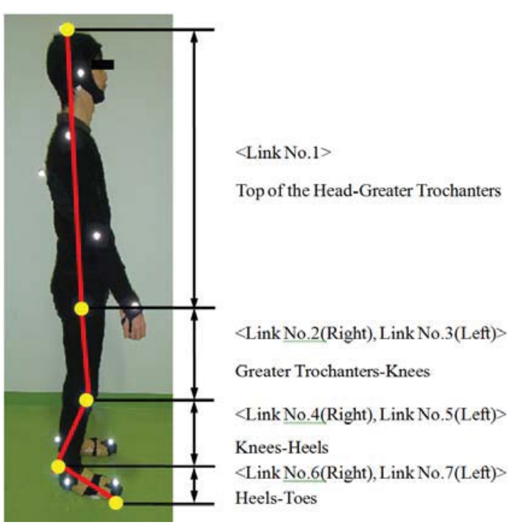


Figure 4. Definition of each link.

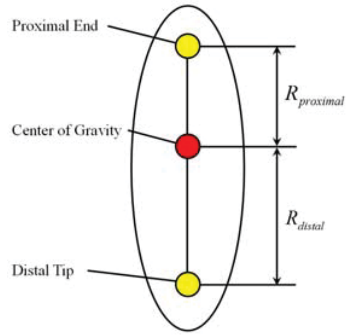


Figure 5. Center point and gravity point of body segment.

IV. Analytical Results and Consideration

A. Singular Value Decomposition of one gait cycle

As for each contributing rate of gait motion pattern, for example, in the analytical results, it is thought that one gait cycle is mainly composed of first mode, second mode and third mode because the sum of these modes are larger than 95 [%] as shown in Fig. 6 and Fig. 7. Then, first, second and third modes are focused in each analytical result of one gait cycle.

Next, each spatial coordination pattern in one gait cycle is as shown in Fig. 8 and Fig. 9. It is thought that first mode is the motion to move the leg forward and back, second mode is plantar flexion and dorsiflexion of ankle joint mainly and third mode is the motion to lift the leg including flexion and extension of knee joint mainly.

B. Singular Value Decomposition of each phase

As for each contributing rate of gait motion pattern, for example, in the analytical results, it is thought that each phase is mainly composed of first mode because first mode is larger than 95 [%] as shown in Fig. 10 and Fig. 11. Then, first mode is focused in the analytical results of each phase.

Next, spatial coordination patterns in each phase are shown in Figs. 12-19 as example of the analytical results. It is thought that first mode is the motion to move the leg forward and back, particularly, plantar flexion and dorsiflexion of ankle joint are mainly composed by this motion. Thus, there are the differences concerning rate of spatial coordination pattern of right knee joint in first phase between healthy subjects and trans-femoral amputee as shown in Fig. 12 and Fig. 16 because of the impossibility of flexion of trans-femoral prosthetic knee joint in first phase opposite to healthy subjects. Furthermore, there are the differences concerning positive and negative value of spatial coordination pattern of right knee joint in third phase between healthy subjects and trans-femoral amputee as shown in Fig. 14 and Fig. 18 for the same reason.

Moreover, trajectories of gravity point correspond to vertical direction in gait motion are as shown in Fig. 20 and Fig. 21. It is clarified that second phases have the differences of behaviors between healthy subjects and trans-femoral amputee. This means that there are differences between supporting leg of the sound limb and one of the prosthetic limb in the displacement of gravity point correspond to vertical direction. It is thought that trans-femoral amputee cannot shift smooth trajectories of gravity point like healthy subjects because of the unstable factor of gravity point by the impossibility of flexion in right amputated leg as supporting leg and fast velocity of the sound limb in the swing phase.

Finally, spatial coordination patterns in second phase of second mode are as shown in Fig. 22 and Fig. 23. It is thought that knee joint of left sound limb in the swing phase has large influence because of value of rate.

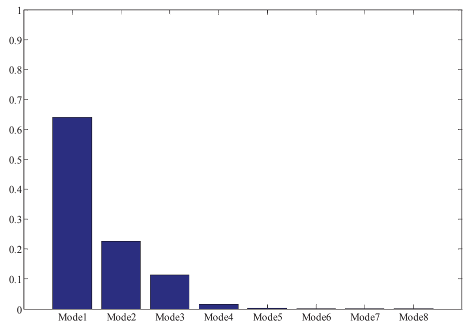


Figure 6. Contributing rate in one gait cycle (T.A.).

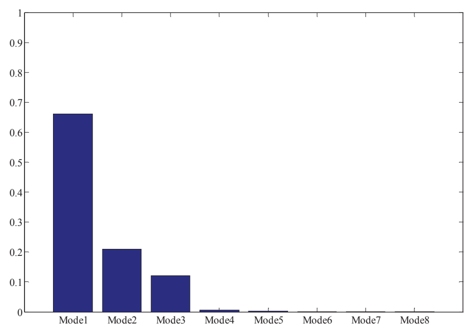


Figure 7. Contributing rate in one gait cycle (H.S.).

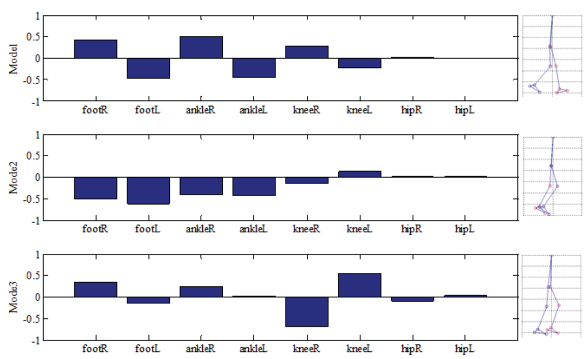


Figure 8. Spatial coordination pattern in one gait cycle (T.A.).

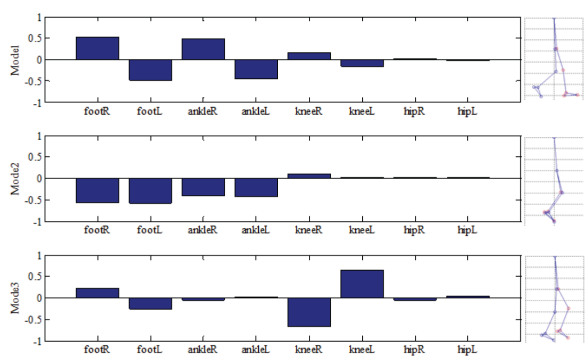


Figure 9. Spatial coordination pattern in one gait cycle (H.S.).

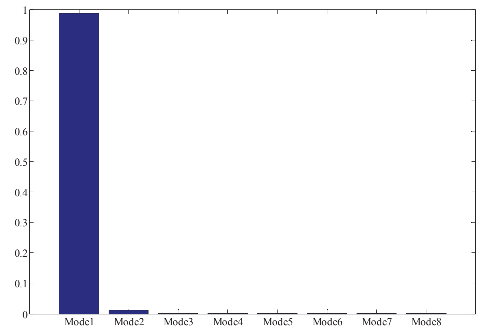


Figure 10. Contributing rate in phase 1 (T.A.).

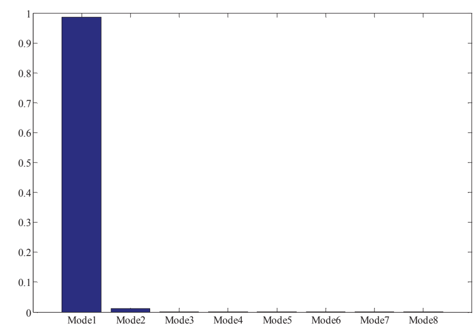


Figure 11. Contributing rate in phase 1 (H.S.).

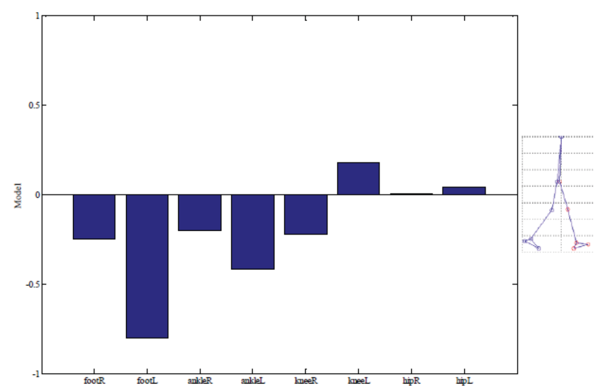


Figure 12. Spatial coordination pattern of mode 1 in phase 1 (T.A.).

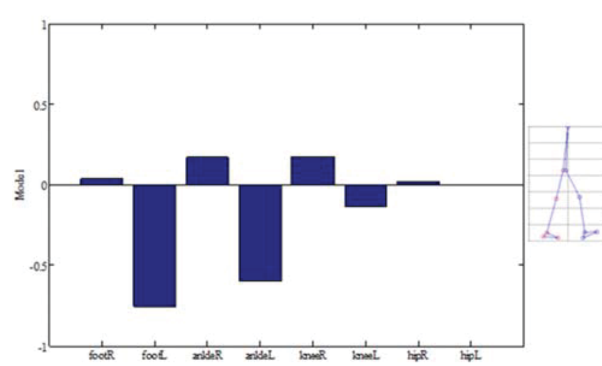


Figure 13. Spatial coordination pattern of mode 1 in phase 2 (T.A.).

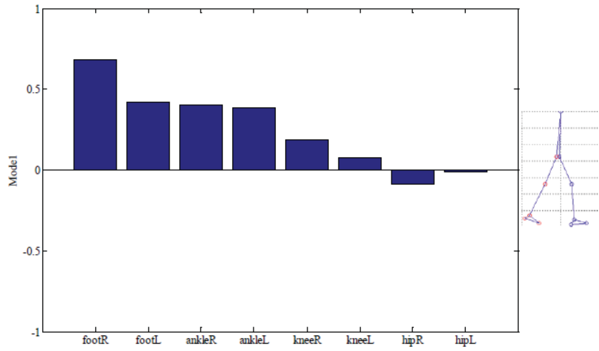


Figure 14. Spatial coordination pattern of mode 1 in phase 3 (T.A.).

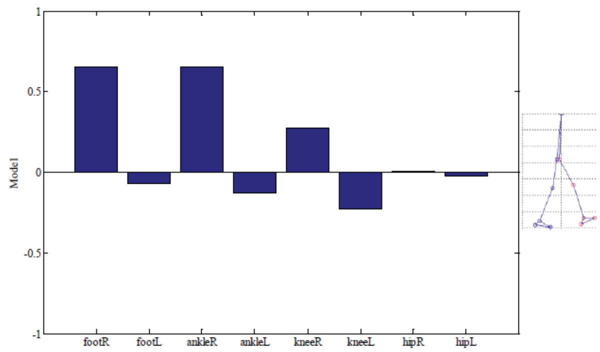


Figure 15. Spatial coordination pattern of mode 1 in phase 4 (T.A.).

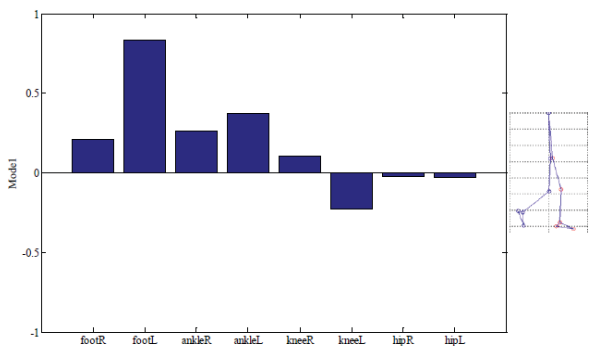


Figure 16. Spatial coordination pattern of mode 1 in phase 1 (H.S.).

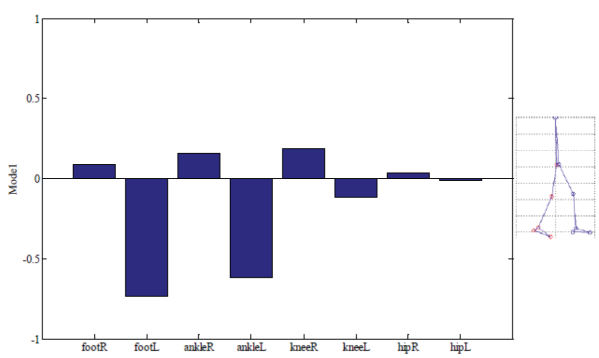


Figure 17. Spatial coordination pattern of mode 1 in phase 2 (H.S.).

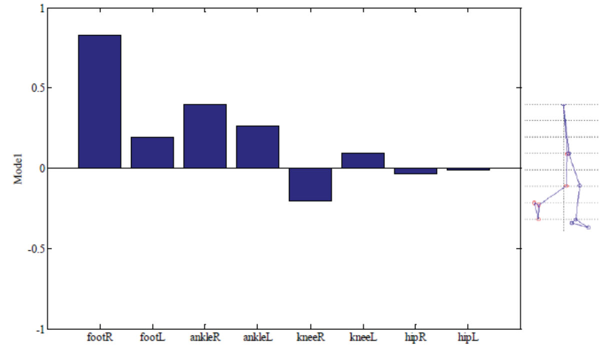


Figure 18. Spatial coordination pattern of mode 1 in phase 3 (H.S.).

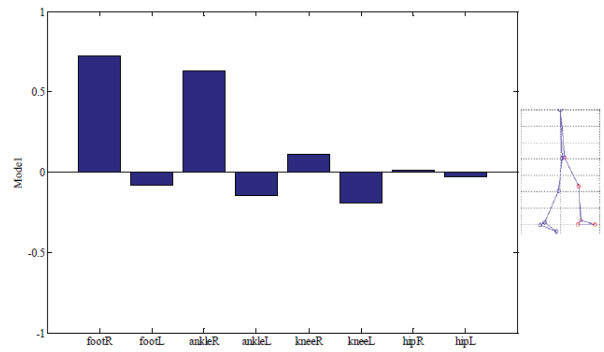


Figure 19. Spatial coordination pattern of mode 1 in phase 4 (H.S.).

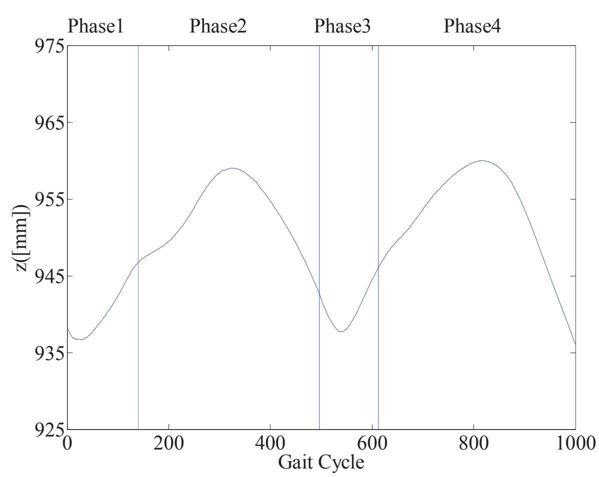


Figure 20. Trajectory of gravity point (T.A.).

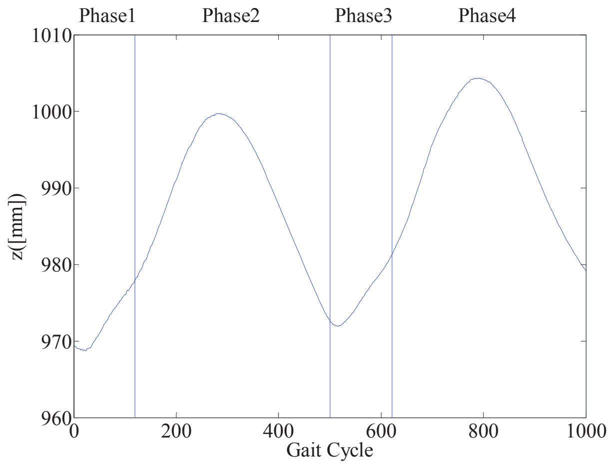


Figure 21. Trajectory of gravity point (H.S.).

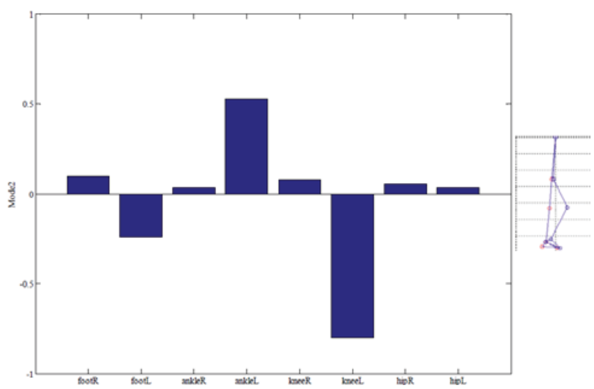


Figure 22. Spatial coordination pattern of mode 2 in phase 2 (T.A.).

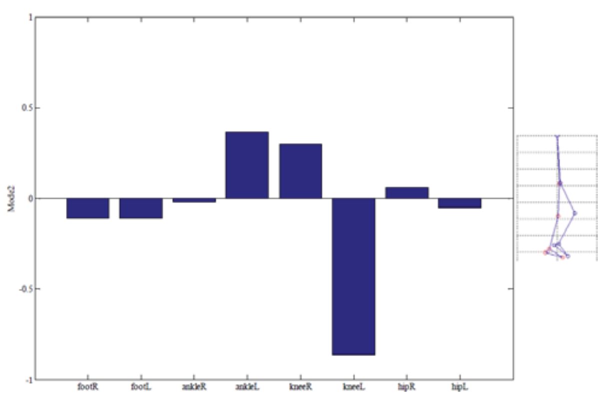


Figure 23. Spatial coordination pattern of mode 2 in phase 2 (H.S.).

V. Conclusion

In this paper, gait measurement is experimented by healthy subjects and trans-femoral amputee with the prosthetic limb. Next, the evaluation method of intersegmental coordination pattern based on singular value decomposition of calculated joint angles is applied to obtained experimental results and trajectories of gravity point are obtained. Meanwhile, quantitative evaluation is performed by comparative verification of each subject from the perspective of constitutive principle. As a result of the analysis, the motion pattern has a high correlation in the intersegmental coordination which is extracted among such physical quantities of healthy subjects and trans-femoral amputee with the prosthetic limb in gait motion by using singular value decomposition. In the end, the effectiveness of the quantitative evaluation based on the kinematic consideration of each joint angle, as well as biomechanics, is validated.

Acknowledgment

This work was partially supported by Grant-in-Aid for Scientific Research (B) (25289053), Japan Society for the Promotion of Science.

References

[1] T. Kitamura, N. Tsujiuchi and T. Koizumi, "Manipulation of Robot Hand Based on Motion Estimation Using EMG Signals," *Transactions of the Japan Society of Mechanical Engineers, Series C*, vol. 73, no. 735, pp. 3024-3030, 2007.

[2] Y. Hayashi, N. Tsujiuchi, T. Koizumi, Y. Matsuda and Y. Tsuchiya, "Biomechanical Consideration Based on the Unrestrained Gait Measurement in Trans-Femoral Amputee with a Prosthetic Limb," *Transactions of the Japan Society of Mechanical Engineers, Series C*, vol. 77, no. 784, pp. 4619-4629, 2011.

[3] M. Schmid, G. Beltrami, D. Zambarbieri and G. Verni, "Centre of pressure displacements in trans–femoral amputees during gait," *Gait & Posture,* vol. 21, no. 3, pp. 255-262, 2005.

[4] T. S. Bae, K. Choi, D. Hong and M. Mun, "Dynamic analysis of above-knee amputee gait," *Clinical Biomechanics*, vol. 22, no. 5, pp. 557-566, 2007.

[5] W. C. C. Lee, L. A. Frossard, K. Hagberg, E. Haggstrom, R. Brånemark, J. H. Evans and M. J. Pearcy, "Kinetics of transfemoral amputees with osseointegrated fixation performing common activities of daily living," *Clinical Biomechanics*, vol. 22, no. 6, pp. 665-673, 2007.

[6] H. G. van Keeken, A. H. Vrieling, A. L. Hof , J. P. K. Halbertsma, T. Schoppen, K. Postema and B. Otten, "Controlling propulsive forces in gait initiation in transfemoral amputees," *Journal of Biomechanical Engineering*, vol. 130, no. 1, pp. 1-9, 2008.

[7] S. Suzuki, "Analytical Study on Control of Above-Knee Prosthesis in Swing Phase," *Transactions of the Japan Society of Mechanical Engineers, Series C,* vol. 70, no. 695, pp. 2110-2117, 2004.

[8] S. Suzuki, "Experimental Study on an Active Knee Joint Mechanism without an External Energy Source," *Transactions of the Japan Society of Mechanical Engineers, Series C,* vol. 75, no. 756, pp. 2274-2279, 2009.

[9] Y. Hayashi, N. Tsujiuchi, T. Koizumi, Y. Matsuda, Y. Tsuchiya and Y. Inoue, "Unrestrained Human Gait Motion Analysis of Healthy Subjects and Trans-Femoral Amputee Using Mobile Force Plate," *Transactions of the Japan Society of Mechanical Engineers, Series C*, vol. 79, no. 805, pp. 3059-3074, 2013.

[10] Y. P. Ivanenko, A. d'Avella, R. E. Poppele and F. Lacquaniti, "On the Origin of Planar Covariation of Elevation Angles during Human Locomotion," *Journal of Neurophysiology*, vol. 99, no. 4, pp. 1890-1898, 2008.

[11] T. Funato, S. Aoi and K. Tsuchiya, "Quantitative Evaluation of the Intersegmental Coordination during Human Locomotion," *Journal of the Robotics Society of Japan*, vol. 28, no. 8, pp. 996-1003, 2010.

[12] T. Funato, S. Aoi, H. Oshima and K. Tsuchiya, "Variant and Invariant Patterns Embedded in Human Locomotion through Whole Body Kinematic Coordination," *Experimental Brain Research*, vol. 205, no. 4, pp. 497-511, 2010.

[13] T. Funato, S. Aoi, N. Tomita and K. Tsuchiya, "Constructive Approach towards Understanding the Control Structure of Human Locomotion based on Kinematic Synergies," *Journal of the Robotics Society of Japan*, vol. 31, no. 8, pp. 739-746, 2013.