33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

Biomechanical Consideration Based on the Unrestrained Gait Measurement of Trans-Femoral Amputee with a Prosthetic Limb

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Abstract— **Trans-femoral amputees must regain moving pattern by refined rehabilitation program using loads applied on a prosthetic limb. On the other hand, understanding those loads is indispensable for biomechanical consideration of trans-femoral amputees. However, conventional prosthetic gait training systems cannot measure long continuous walking motions. In this paper, loads applied on trans-femoral prosthesis are measured by the prosthetic gait training system for the unrestrained gait measurement. As a result of the experiments, the patterns of moments about the medio-lateral axis are remarkably different among the six activities. Finally, the effectiveness of the developed prosthetic gait training system to analyze biomechanics in trans-femoral prosthesis is validated.**

I. Introduction

Trans-femoral prosthesis that is used by the amputees has the artificial knee joint as an alternative function of a knee to secure stability during stance phase and swing phase [1]–[2]. In this case, performance of the artificial knee joint highly affects activities and a cure of the amputees. Then, they must regain moving pattern by refined gait training using load conditions on a prosthetic limb as quantitative evaluation indices for the rehabilitation program [3]. Hence, it is essential to understand loads applied on a prosthetic limb for this goal and biomechanical consideration of the artificial knee joint with walking control function [4]–[7]. However, conventional prosthetic gait training systems cannot measure long continuous walking motions outdoors. Therefore, we have developed a novel six-axis force/moment sensor attached to a prosthetic limb for the unrestrained gait measurement [8].

In this paper, loads applied on the intermediate part between the prosthetic knee joint and the ankle joint of a trans-femoral amputee with a prosthetic limb are measured by the prosthetic gait training system using the developed sensor. At that time, activities which include straight-line walking on level and uneven ground, negotiating stairs, going up and down slope are experimented. Load patterns along each gait cycle, magnitudes and occurrence times of loads are analyzed. Finally, the effectiveness of the developed prosthetic gait training system to understand biomechanics in trans-femoral prosthesis during gait and refine the rehabilitation program for the amputees is validated.

II. Experimental Methodology

A. Subject and Trans-Femoral Prosthesis

In this study, one male unilateral trans-femoral amputee with a prosthetic limb participates. The details of this subject are shown in Table 1. He has worn a prosthetic limb for at least 27 years. The total mass includes body mass plus the mass of a prosthetic limb. The experiments take place in an outdoor environment at Doshisha University, Kyoto, Japan. Human research ethical approval is received from Doshisha University and written consent is obtained from this subject. This subject has been fitted with his trans-femoral prosthesis of normal socket-type by a prosthetist who can replicate the stable alignment of a prosthetic limb.

TABLE I
SUBJECT CHARACTERISTICS

Gender (Male/Female)	Male
Age (Years)	30
Height [m]	1.70 [m]
Total Mass [kg]	75.7 [kg]
Side of Amputation (Right/Left)	Right
Footwear	Running Shoes
Prosthetic Foot	Vari-Flex
Prosthetic Knee	Total Knee 2100

B. Experimental Facility

The instrument to directly measure loads applied on the intermediate part of a prosthetic limb is the developed eight-channel six-axis force/moment sensor as shown in Fig. 1. This sensor features integration of measuring section and signal processing section by embedded data logger and can measure long continuous data without PC by battery and memory card. Moreover, this sensor is fixed between prosthetic knee joint and ankle joint on the long axis (L, equivalent to z-axis) as shown in Fig. 2. The other axes correspond to the anatomical antero-posterior (AP, equivalent to x-axis) and medio-lateral (ML, equivalent to y-axis) direction as shown in Fig. 3. Forces applying along each axis and moments about each one are expressed as F_{AP} (anterior is positive), F_{ML} (medial is positive), F_{L} (compression is positive), M_{AP} (lateral rotation is positive), M_{ML} (posterior rotation is positive) and M_{L} (external rotation is positive), respectively [4]. The rating capacity of this sensor is 1,000 [N] for forces, and 50 [N·m] for M_{L}, 100 [N·m] for M_{AP} and M_{ML} about each axis are as shown in Table 2. Furthermore, sampling frequency is 1,000 [Hz].

TABLE II
STANDARD OF A SIX-AXIS FORCE/MOMENT SENSOR

Rating Capacity	$F_x,\ F_y,\ F_z = 1000$ [N] $M_x,\ M_y = 100$ [N·m] $M_z = 50$ [N·m]
Material	A7075/A2024

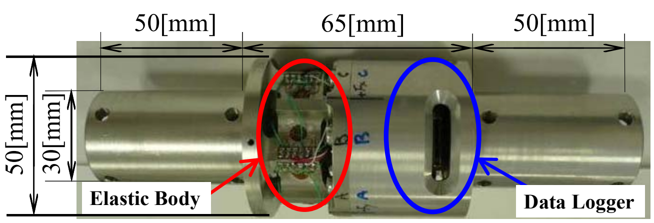

Fig. 1. Prototype of a six-axis force/moment sensor.

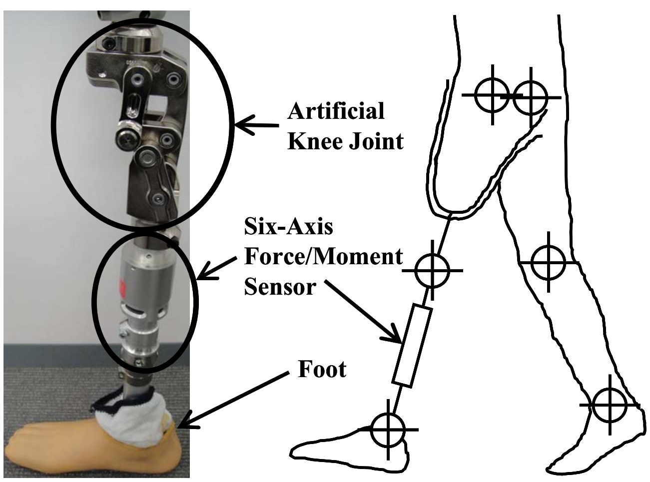

Fig. 2. Attachment position of a six-axis force/moment sensor.

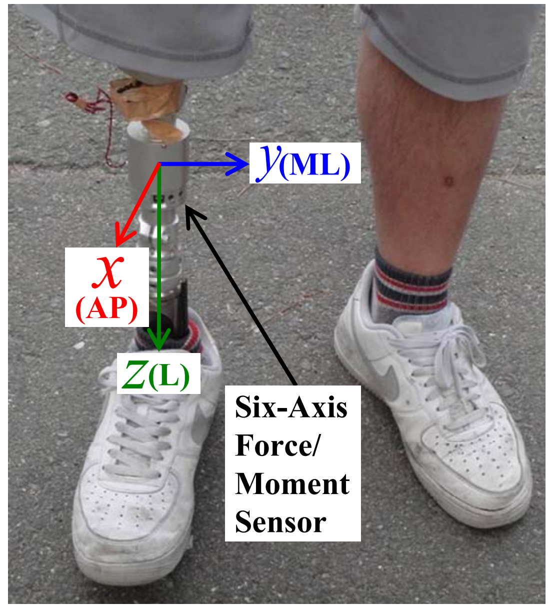

Fig. 3. Each coordinate axis direction of the prosthetic gait training system.

C. Experiment Description

The subject perform each activity of straight-line walking on level and uneven ground, walking upstairs, downstairs, upslope and downslope. Descriptions of each activity are concretely shown in Table 3. Actually, about 20 [min] of practice with the prosthetic gait training system is performed before the experiments to evidence this confidence. Loads are measured for at least fifteen steps of each activity when the subject walks at a self-selected speed because of the unrestrained gait measurement.

TABLE III
DESCRIPTIONS OF EACH ACTIVITY IN THE EXPERIMENTS

Activities	Descriptions
Level Walking	Level walking along a level, straight-line walkway
Uneven Ground Walking	Level walking along an uneven ground, straight-line walkway
Downslope	Descending 10 [deg] of a slope
Upslope	Ascending 10 [deg] of a slope
Downstairs	Descending stairs of 0.18 [m] height × 0.32 [m] deep
Upstairs	Ascending stairs of 0.18 [m] height × 0.32 [m] deep

D. Data Analysis

Obtained patterns of loads for each gait cycle of the various activities are analyzed when the first and last steps recorded for each trial are eliminated to avoid the initiation and termination of walking. The stance phase and the swing phase are determined by the curve behavior of F_{L}. Gait cycle is defined as the period between two consecutive heel contacts. In addition, magnitudes and occurrence times of loads are determined for each step of a prosthetic limb. Resultant forces F_{R} are calculated by the vector synthesis of F_{AP}, F_{ML} and F_{L}.

III. Experimental Results and Consideration

Figures 4-5 show the patterns of forces and moments obtained from the experiments in straight-line level walking by way of example in the results. It can be seen that each force follows a similar pattern to the ground reaction forces obtained by a force plate [7]. As expected, long axis force has the largest magnitude. First, some posterior braking forces are applied by heel contact at the earlier stance phase and anterior propulsive forces are applied by toe off at the later stance phase during level walking. Moreover, some lateral forces and lateral rotational moment are applied at the entire stance phase. Besides, anterior rotational moment is applied during the earlier stance phase and posterior rotational moment at the later stance phase because the artificial knee joint is unlocked. Since inertial forces are created by gravity of the leg region and the acceleration of the artificial knee joint, loads have small magnitudes at the entire swing phase except for the long axis. On the one hand, walking on uneven ground has similar patterns of loads to level walking as shown in Figs. 6-7.

Secondly, it can be seen that the patterns of loads resemble to those of level walking except for F_{AP}, M_{ML} and M_{L} when performing the other activities. Figures 8-9 show the patterns of forces obtained from the experiments when upstairs and downstairs by way of example in the results. Anterior and posterior forces have small magnitudes at the entire stance phase when walking downstairs. Moreover, unlike level walking with some posterior forces applied at the earlier stance phase and anterior forces at the later stance phase, anterior forces are applied at the entire stance phase when walking upstairs. These results may be explained by a sense of insecurity on the stairs. Patterns of forces for a slope follow those for level walking and inconsistent moments about the long axis are applied throughout the experiments.

Thirdly, Figures 10-13 show the patterns of moments when going up and down slope, negotiating stairs by way of example in the results. Posterior rotational moment is applied at the entire stance phase when walking upslope and upstairs. Then, anterior rotational moment is applied during the earlier stance phase and posterior rotational moment is applied at the later stance phase when walking downslope. However, walking downstairs has no peak of posterior rotation moment. Therefore, the patterns of moments about the medio-lateral axis are remarkably different among the six activities.

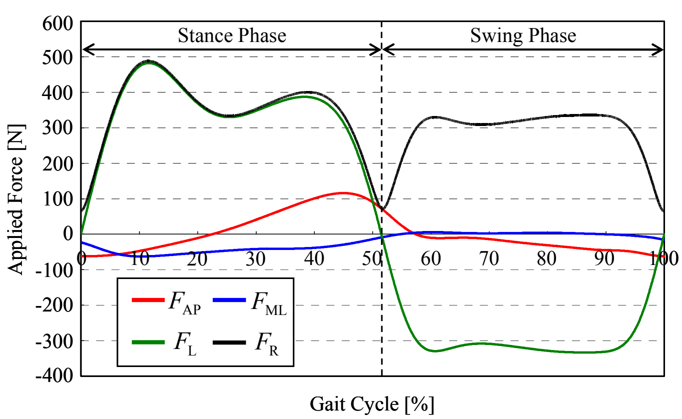

Fig. 4. Patterns of forces along a gait cycle in straight-line level walking.

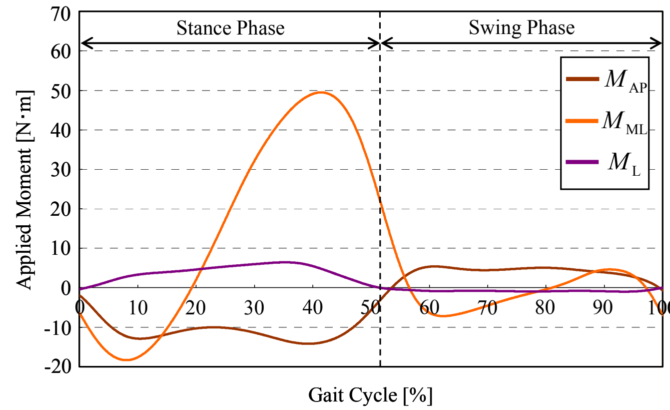

Fig. 5. Patterns of moments along a gait cycle in straight-line level walking.

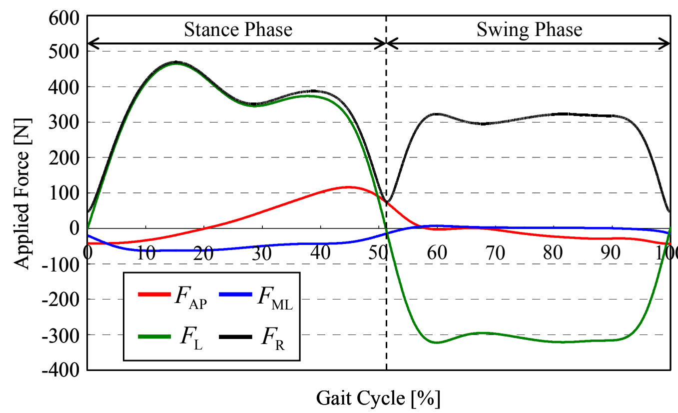

Fig. 6. Patterns of forces along a gait cycle in uneven ground walking.

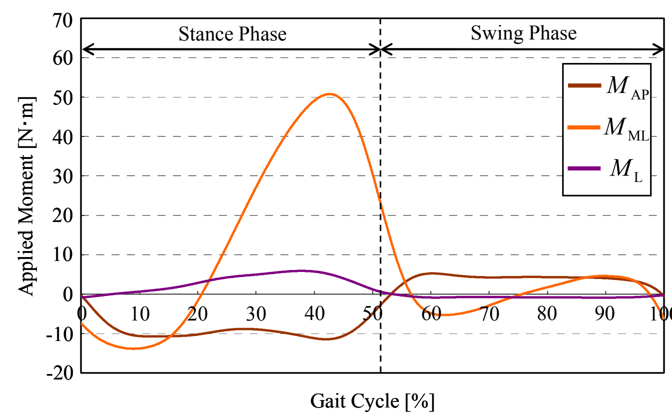

Fig. 7. Patterns of moments along a gait cycle in uneven ground walking.

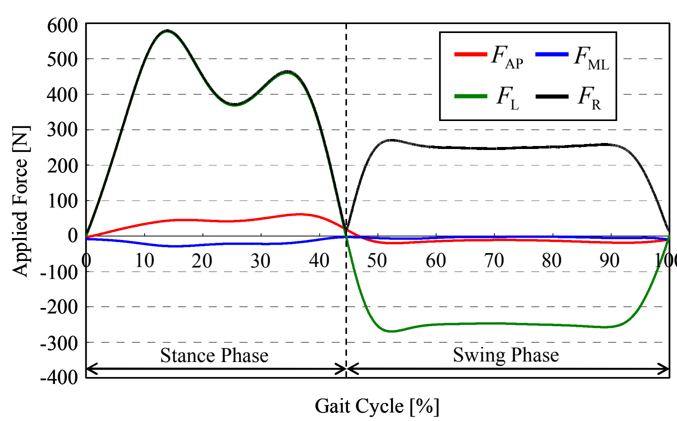

Fig. 8. Patterns of forces along a gait cycle in walking upstairs.

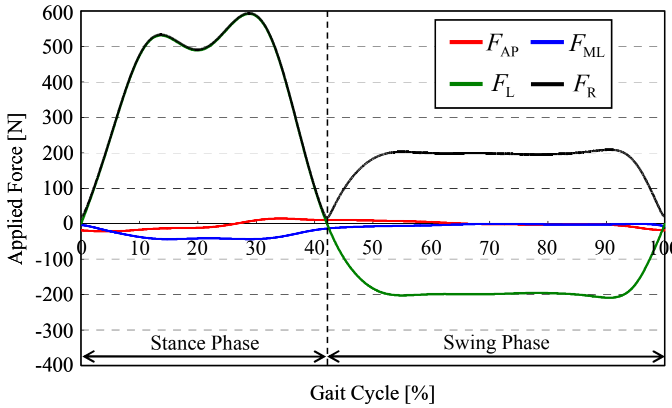

Fig. 9. Patterns of forces along a gait cycle in walking downstairs.

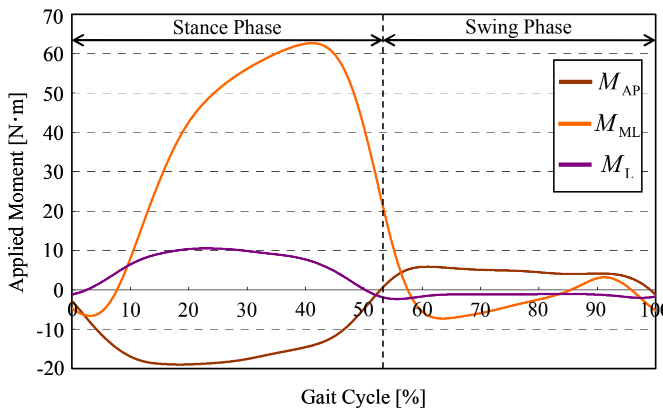

Fig. 10. Patterns of moments along a gait cycle in walking upslope.

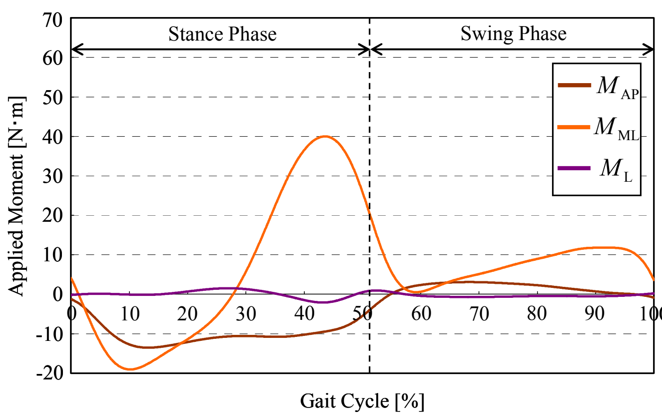

Fig. 11. Patterns of moments along a gait cycle in walking downslope.

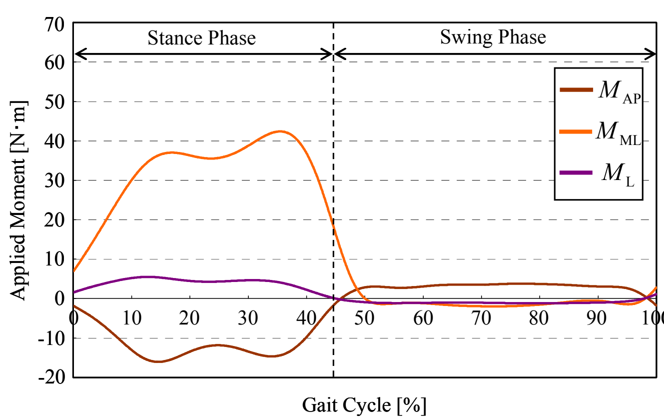

Fig. 12. Patterns of moments along a gait cycle in walking upstairs.

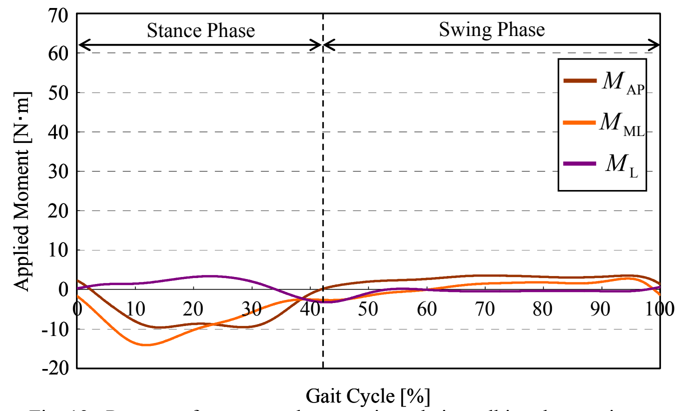

Fig. 13. Patterns of moments along a gait cycle in walking downstairs.

IV. Conclusion

In this paper, loads applied on a prosthetic limb of a trans-femoral amputee performing six different activities are measured by the prosthetic gait training system using a novel six-axis force/moment sensor for the unrestrained gait measurement. Obtained loads are compared to clarify their biomechanical behaviors. As a result of the experiments, magnitudes and occurrence times as well as the curve patterns of each axial load for each gait cycle are revealed. The patterns of moments about the medio-lateral axis explain that different strategies are used to control the prosthetic knee joint for different activities. Overall, the effectiveness of the developed prosthetic gait training system to understand biomechanics in trans-femoral prosthesis during gait and refine the rehabilitation program is validated.

Acknowledgment

This study was partially supported by Grant-in-Aid for Scientific Research (A)(23246041), Japan Society for the Promotion of Science.

References

[1] 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. 222–229, 2004.

[2] 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. 180–185, 2009.

[3] M. Schmid, G. Beltrami, D. Zambarbieri and G. Verni, "Centre of pressure displacements in trans–femoral amputees during gait," *Gait and Posture*, vol. 21, pp. 255–262, 2005.

[4] W. C. C. Lee, L. A. Frossard, K. Hagberg, E. Haggstrom, R. Branemark, J. H. Evans and M. J. Pearcy, "Kinetics of transfemoral amputees with osseointegrated fixation performing common activities of daily living," *Clinical Biomechanics*, vol. 22, pp. 665–673, 2007.

[5] W. C. C. Lee, L. A. Frossard, K. Hagberg, E. Haggstrom, D. L. Gow, S. Gray and R. Branemark, "Magnitude and variability of loading on the osseointegrated implant of transfemoral amputees during walking," *Medical Engineering & Physics*, vol. 30, pp. 825–833, 2008.

[6] T. S. Bae, K. Choi, D. Hong and M. Mun, "Dynamic analysis of above-knee amputee gait," *Clinical Biomechanics*, vol. 22, pp. 557–566, 2007.

[7] 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, pp. 1–9, 2008.

[8] Y. Hayashi, N. Tsujiuchi, T. Koizumi, H. Oshima, A. Ito and Y. Tsuchiya, "Proposal of structural optimization method for a six-axis force/moment sensor attached to a prosthetic limb," *Proceedings of the 10th International Conference on Motion and Vibration Control*, 2010.