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# Gait Motion Analysis in the Unrestrained Condition 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 ground reaction forces, joint angles and joint moments applied on a prosthetic limb. On the other hand, understanding those loads and kinematic variables is indispensable for gait analysis based on the biomechanical consideration of trans-femoral amputees. However, conventional prosthetic gait training systems cannot measure long continuous walking motions. In this paper, ground reaction forces and kinematic parameters applied on trans-femoral prosthesis are measured by the prosthetic gait motion analysis system using mobile force plate and attitude sensor for the unrestrained gait measurement. As a result of the experiments, the patterns of antero-posterior axis ground reaction forces and joint moments about the medio-lateral axis are remarkably different among the five activities. Finally, the effectiveness of the developed prosthetic gait training system to consider biomechanics and kinematics in trans-femoral prosthesis is validated.**

## I. INTRODUCTION

Several studies have investigated trans-femoral prosthetic gait with the artificial knee joint as an alternative function of a knee to control stance phase and swing phase [1, 2]. In this case, it can be important to pay attention to biomechanical characteristics of each joint in trans-femoral prosthesis. On the one hand, it is thought that trans-femoral amputees must regain moving pattern by gait training using kinematic conditions on a prosthetic limb as quantitative evaluation indices to improve their rehabilitation program [3]. For these reasons, our previous studies have suggested a novel six-axis force/moment sensor attached to a prosthetic limb for the unrestrained gait measurement [4, 5]. However, the developed sensor cannot evaluate an asymmetry of trans-femoral prosthetic gait. Besides, it cannot consider ground reaction forces and joint angles. Therefore, we have developed the wearable gait motion analysis system [6] using mobile force plate and attitude sensor as the prosthetic gait training system.

In this paper, ground reaction forces and kinematic parameters such as ankle joint moment applied on the lower limb are measured under a wide range of environmental conditions reflected activities of daily living by the developed system. In particular, activities which include straight-line walking on level, upslope, downslope, upstairs and down stairs are experimented. Load and kinematic mechanisms along each gait cycle as intercomparison of amputated limb with sound limb are analyzed. Finally, the effectiveness of the developed wearable gait motion analysis system to understand biomechanics in trans-femoral prosthetic gait and evaluate an asymmetry of the amputees during gait is validated.

## II. EXPERIMENTAL METHODOLOGY

### A. Subject and Trans-Femoral Prosthesis

In this paper, one male unilateral trans-femoral amputee with a prosthetic limb participates. The characteristics of this subject are as shown in Table 1. He has worn the trans-femoral prosthesis of normal socket-type for at least 29 years. The total mass includes body mass plus the mass of a prosthetic limb. The experiments take place at Doshisha University, Kyoto, Japan. Human research ethical approval is received from Doshisha University and written consent is obtained from this subject.

TABLE I
SUBJECT CHARACTERISTICS

| Gender (Male/Female) | Male |
|---|---|
| Age (Years) | 31 |
| Height [m] | 1.70 [m] |
| Total Mass [kg] | 73.0 [kg] |
| Side of Amputation (Right/Left) | Right |
| Footwear | Running Shoes |
| Prosthetic Foot | Vari-Flex |
| Prosthetic Knee | Total Knee 2100 |

### B. Experimental Facility

The experimental facility for measuring ground reaction forces and joint moments applied on a sound limb and a prosthetic limb of the subject is the developed wearable gait motion analysis system as shown in Fig. 1. This system consists of mobile force plate using the thin-type three-axis

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force sensor and attitude sensor structured by acceleration, gyro, and geomagnetism sensor. Moreover, the former mobile force plate is fixed beneath a pair of sandals. This system has less cost and fewer constraints. The experimental data measured by mobile force plate and attitude sensor are transferred to PC via data logger by wireless LAN and recorded on the laptop PC. In gait experiments, ground reaction force, center of pressure, joint angle, joint moment and limb postures can be calculated by the outputs of mobile force plate and attitude sensor.

In the definition of coordinate system, forces and moments regarding x, y and z-axes directions are defined as $F_x$, $F_y$, $F_z$ and $M_x, M_y, M_z$ when the positive rotation of each axis is clockwise and coordinate systems are right-handed. Specifically, x, y and z-axes correspond to the anatomical medio-lateral (lateral is positive), antero-posterior (anterior is positive) and vertical (upward is positive) directions. It is identified that the original point of the total coordinate system in a one-sided foot with the original point of the coordinate system in the heel-side mobile force plate.

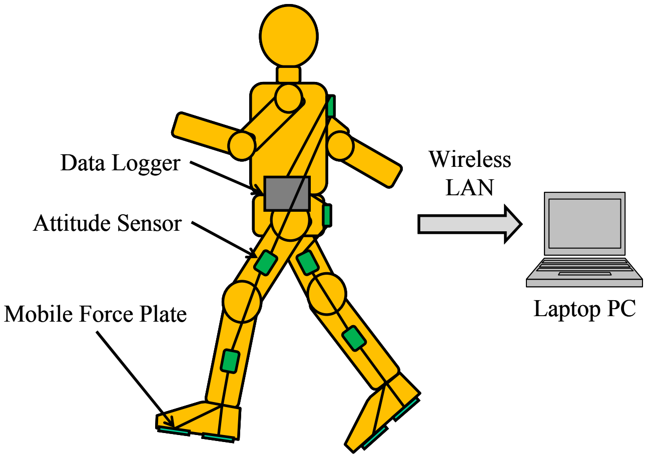


Fig. 1. Constitution of the developed wearable gait motion analysis system.

## C. Experiment Description

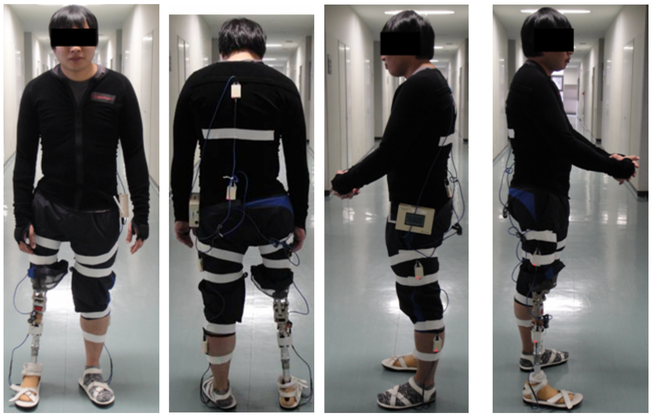
The subject performs each activity of straight-line walking on level, walking upstairs, downstairs, upslope and downslope. Descriptions of each activity and the experimental fields are concretely as shown in Table 2 and Fig. 2. Actually, about 20 [min] of practice is performed before the experiments. Ground reaction forces and kinematic parameters are measured for at least 10 steps of each activity when the subject walks at a self-selected speed because of the unrestrained gait measurement as shown in Fig. 3. Sampling frequency and cut-off frequency of low-pass filter in the experimental facility are 100 [Hz] and 10 [Hz].

TABLE II
DESCRIPTIONS OF EACH ACTIVITY IN THE EXPERIMENTS

| Activities | Descriptions |
|---|---|
| Level Walking | Level walking along a level, straight-line walkway |
| Downslope | Descending 5 [deg] of a slope |
| Upslope | Ascending 5 [deg] of a slope |
| Downstairs | Descending stairs of 0.175 [m] height × 0.3 [m] deep |
| Upstairs | Ascending stairs of 0.175 [m] height × 0.3 [m] deep |

(a) Level (b) Slope (c) Stairs

Fig. 2. Experimental fields.



(a) Front view (b) Back view (c) Left side view (d) Right side view

Fig. 3. Subject with the wearable gait motion analysis system.

## D. Data Analysis

Obtained patterns of ground reaction forces and kinematic parameters 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 $F_z$. Gait cycle is defined as the period between two consecutive heel contacts.

In a one-sided right foot, all ground reaction forces $\boldsymbol{F} = (F_x \quad F_y \quad F_z)^T$ are as follows when toe-side and heel-side are expressed by suffixes *toe* and *heel*. Hereafter, ground reaction forces and moments of toe-side and heel-side are $\boldsymbol{F}'_{toe}, \boldsymbol{F}'_{heel}, \boldsymbol{M}'_{toe}, \boldsymbol{M}'_{heel}$ .

$$\boldsymbol{F} = \begin{pmatrix} F_x \\ F_y \\ F_z \end{pmatrix} = \begin{pmatrix} F'_{x\,toe} + F'_{x\,heel} \\ F'_{y\,toe} + F'_{y\,heel} \\ F'_{z\,toe} + F'_{z\,heel} \end{pmatrix} \tag{1}$$

Then, ankle joint moment about x-axis $M_{x\,ankle}$ is as follows. $g, m_{foot}, l_{y1}, l_{y4}, l_{y7}, l_{z1}, l_{z4}, I_{x1}, \ddot{\theta}_{x1}$ are acceleration of gravity, mass of foot, each moment arm on the lower limb, moment of inertia about x-axis of ankle joint, and angular acceleration about x-axis of ankle joint.

$$\begin{aligned} M_{x\,ankle} &= l_{y1}F'_{z\,toe} - l_{z1}F'_{y\,toe} + l_{y4}F'_{z\,heel} - l_{z4}F'_{y\,heel} \\ &\quad - l_{y7}\, m_{foot}\, g + M'_{x\,toe} + M'_{x\,heel} + I_{x1}\,\ddot{\theta}_{x1} \end{aligned} \tag{2}$$

## III. EXPERIMENTAL RESULTS AND CONSIDERATION

### A. *Walking Level and Slope*

Figure 4-7 show the patterns of ground reaction forces and ankle joint moments of sound limb and prosthetic limb obtained from the experiments in straight-line level walking by way of example in the results.

Larger vertical forces of sound limb are applied by heel contact at the earlier stance phase and the occurrence times of peaks regarding dorsiflexion moments are earlier to strongly shift the weight for maintaining natural standing posture. Moreover, anterior forces of prosthetic limb are applied at the entire stance phase because foot of prosthetic limb has no sense of plantar pressure and applying propulsive forces is difficult.

On the one hand, walking upslope and downslope has similar patterns of ground reaction forces and ankle joint moments to straight-line level walking.

### B. *Walking Stairs*

Figures 8-11 show the patterns of ground reaction forces and ankle joint moments of sound limb and prosthetic limb obtained from the experiments when walking upstairs by way of example in the results. The stance phase times of sound limb are longer than ones of prosthetic limb. In addition, constant dorsiflexion moments of sound limb are applied during the entire stance phase. Besides, smaller anterior forces of prosthetic limb are applied at the entire stance phase. These results may be explained by a sense of insecurity on the stairs. Incidentally, inconsistent moments about antero-posterior and vertical axes are applied throughout the experiments.

Figure 12 and Figure 13 show the patterns of ankle joint moments when walking downstairs by way of example in the results. The patterns of ground reaction forces in walking downstairs are obtained as well as walking upstairs. The data of sound limb have longer stance phase time. In particular, dorsiflexion moments of sound limb are applied during the entire stance phase. As for prosthetic limb, smaller plantar flexion moments are applied during the earlier stance phase and smaller dorsiflexion moments are applied at the later stance phase because of insecurity on the stairs. Therefore, in addition to the patterns of propulsive and braking forces, ones of joint moments among the five activities are effective to evaluate an asymmetry of amputee gait.

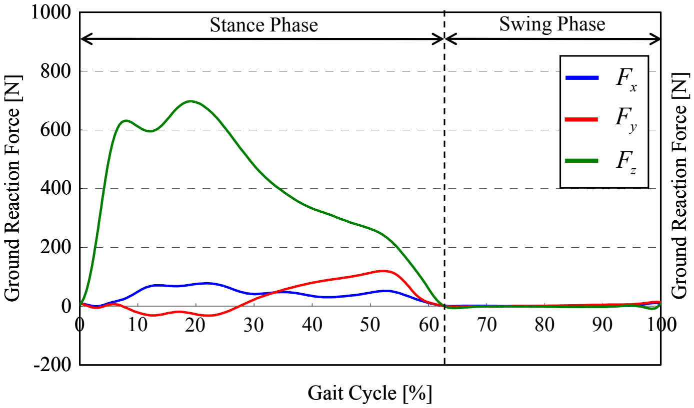


Fig. 4. Ground reaction forces of sound limb in straight-line level walking.

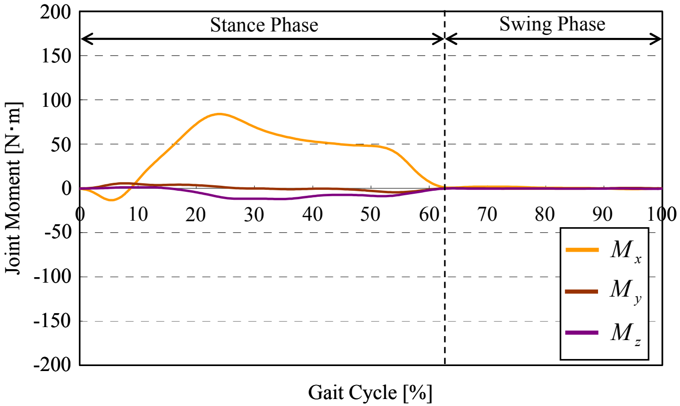


Fig. 5. Ankle joint moments of sound limb in straight-line level walking.

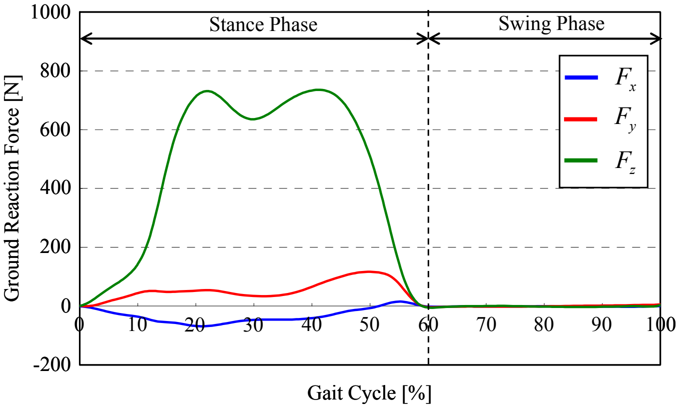


Fig. 6. Ground reaction forces of prosthetic limb in straight-line level walking.

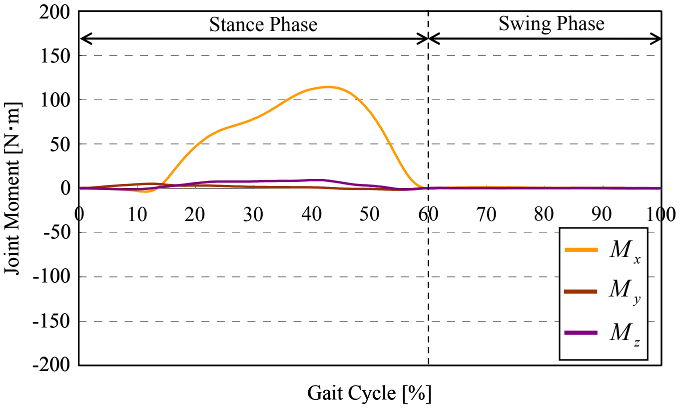


Fig. 7. Ankle joint moments of prosthetic limb in straight-line level walking.

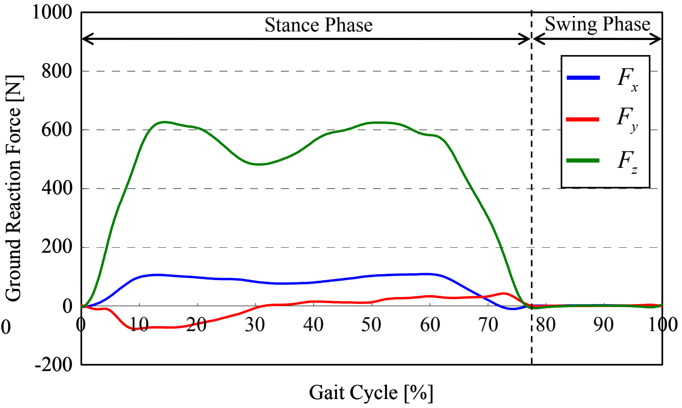


Fig. 8. Ground reaction forces of sound limb in walking upstairs.

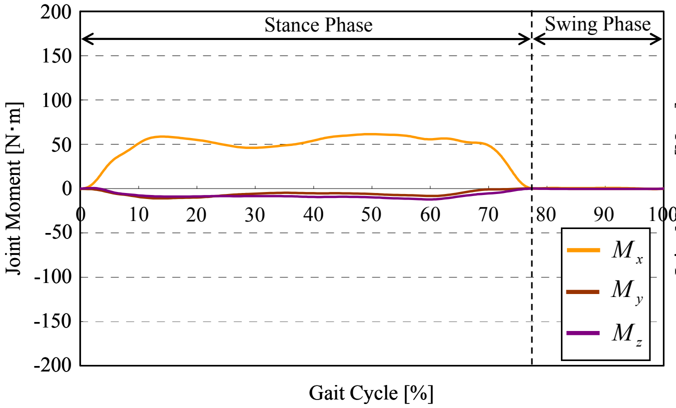


Fig. 9. Ankle joint moments of sound limb in walking upstairs.

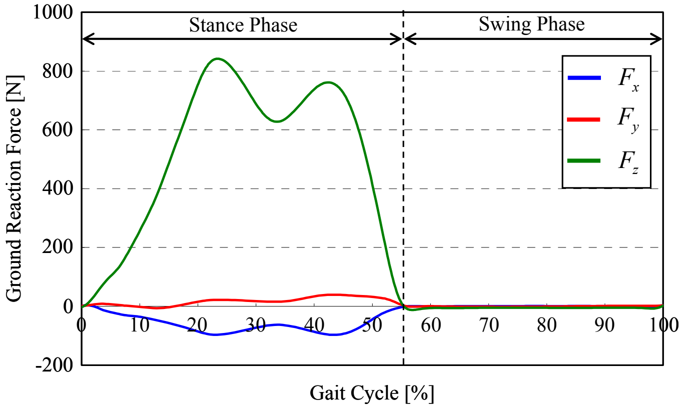


Fig. 10. Ground reaction forces of prosthetic limb in walking upstairs.

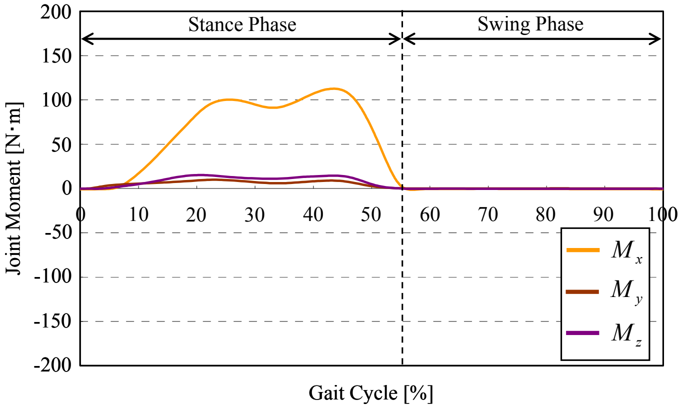


Fig. 11. Ankle joint moments of prosthetic limb in walking upstairs.

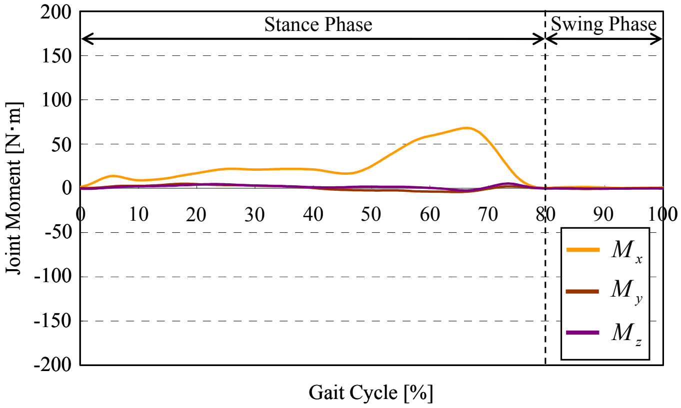


Fig. 12. Ankle joint moments of sound limb in walking downstairs.

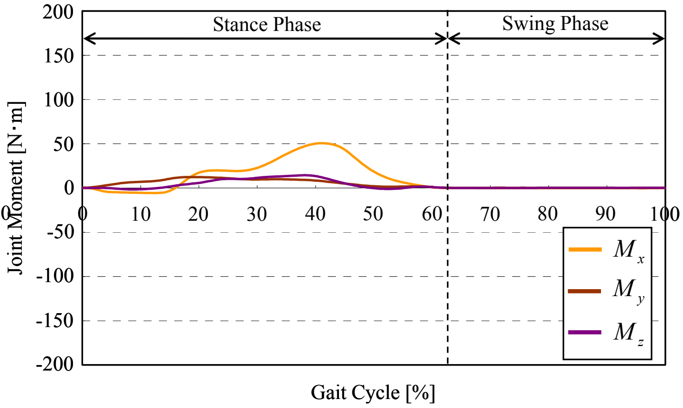


Fig. 13. Ankle joint moments of prosthetic limb in walking downstairs.

## IV. CONCLUSION

In this paper, ground reaction forces and ankle joint moments applied on the lower limb including sound limb and prosthetic limb of a trans-femoral amputee are measured by a novel wearable gait motion analysis system in five terrain conditions. Next, each load component is compared to the others concerning sound limb and amputated limb. As a result of the experiments, in addition to the patterns of propulsive and braking forces, ones of plantar flexion and dorsiflexion joint moments among the five activities are effective to evaluate an asymmetry of amputee gait and control the artificial knee joint for prosthetic gait training. In the end, the effectiveness of the developed wearable gait motion analysis system for the unrestrained gait measurement to analyze and understand biomechanical behaviors in trans-femoral prosthetic gait and quantitatively evaluate them is validated.

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