Analysis of Walking Skill with Trans-Femoral Prosthesis based on Inertia-Induced Measure

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***Abstract* - A method to quantify the walking skill with trans-femoral prosthesis will be explored for better gait rehabilitation and design of prosthesis leg. Inertia of the prosthesis plays an important role in natural and smooth gaits during the swing phase. We suppose that goodness of gait is strongly related to effective use of the prosthesis inertia. So far we have proposed the inertia-induced measure as a new method to quantify the effective use of the inertia property of the prosthesis leg in the swing phase based on Riemannian distance. In this paper, we analyzed walking skill with trans-femoral prosthesis leg based on the inertia-induced measure. Gait of a prosthesis leg user was measured at 5th, 8th, and 15th months after amputation. Changes of gait, inertia-induced measure, and subjective evaluation were investigated.**

Index Terms* – *Trans-femoral prosthesis, Walking, Inertia-induced measure, walking skill.

I. INTRODUCTION

Trans-femoral prosthesis is the prosthetic leg that is used by individuals amputated above their knee. In such a prosthesis, mechanism and control method are important to guarantee safe walking. Recent advancements in the mechanism and the control method of trans-femoral prostheses have drastically improved the gait of amputees and realized safer stance phase of the prosthesis. In particular, computer-controlled trans-femoral prostheses significantly contribute to dramatically increase safety in walking with a prosthesis [1], [2], [3]. In order to realize higher activities of daily living (ADL) of prosthesis users, development of the prosthesis realizing easiness of walking is important. Swing phase of the prosthesis has great impact to easiness of walking / smoothness of gait while function of the knee joint in the stance phase plays very important roles to guarantee safe walking. Thus, computer-controlled prostheses succeed to increase gait smoothness in the swing phase [2], [3], [4].

On the other hand, matching of the prosthesis to the users is important issue to be considered. There are several factors to be matched for instance the socket, alignment, control parameter for computer-controlled prosthesis, and inertia property. One method of evaluate the matching is to investigate the gait by wearing the targeted prosthesis. On the inertia matching, Wada et al. [5] showed that inertia property affects easiness of walking greatly and existence of the appropriate range of the inertia property. Then, we proposed to utilize inertia-induced measure [6] as the index to represent effective use of inertia property of the whole body including the prosthesis in analysis of swing phase gait[5]. In addition, Wada et al.[7] proposed a method to evaluate inertia-matching between the user and the prosthesis using the inertia-induced measure. In these studies, it is found that the skill of the user strongly affect the effective use of the inertia property while these papers did not investigate its effect in detail.

The goal of this research is preliminary investigation on identification of walking skill with the prosthesis toward better gait rehabilitation with the trans-femoral prosthesis and its design methodology. So far, much research has been conducted on evaluating the gait with a prosthesis. For instance, comparative studies of different prostheses have been conducted based on joint angles and joint moments [2] as well as energy consumption in each joint [4] as an application of conventional gait analysis methodology. However, research on quantifying the walking skill with the trans-femoral prosthesis cannot be found.

In this research, gait with the trans-femoral prosthesis is evaluated from the viewpoint of effective use of its inertia property for realizing better rehabilitation technique based on the user's walking skill with the prosthesis. The effective use of the inertia is evaluated by inertia-induced measure[6]. In our previous work, gaits were measured by changing the inertia parameters of the prosthesis by adding a weight on the leg part [9]. The results showed the strong relevance between subjective evaluation of easiness of walking and the degree of inertia-induced motion. In the inertia condition with the best subjective evaluation, the gait is closer to the inertia-induced motion. But, the paper did not deal with transient change of the degree of inertia-induced motion in time even though it can reflect user's skill for prosthesis walk.

In this paper, we will analyze walking skill with trans-femoral prosthesis leg based on the inertia-induced measure. Gait of a prosthesis leg user was measured at 5th, 8th, and 15th months after amputation. Changes of gait, inertia-induced measure, and subjective evaluation were investigated using the inertia-induced measure.

II. Evaluation of Effective Use of Inertia Property in Swing Phase of Prosthesis Walking

A. Model of Swing Phase Walking with Prosthesis

Fig.1 illustrates link segment model of gait with the prosthesis in the swing phase. Assume that motions of the ankle and the knee of the intact end can be ignored. Link 1 denotes the upper and the lower legs. Link 2 denotes the upper leg of the amputated end and the socket part. Link 3 denotes the knee joint, the lower leg, and the foot part of the prosthesis. Link 0 represents the human's whole trunk. Assume that link 0 is vertical through walking. Angle q_1 denotes the ankle joint of the intact end and it is assumed that the ankle joint is fixed at the floor.

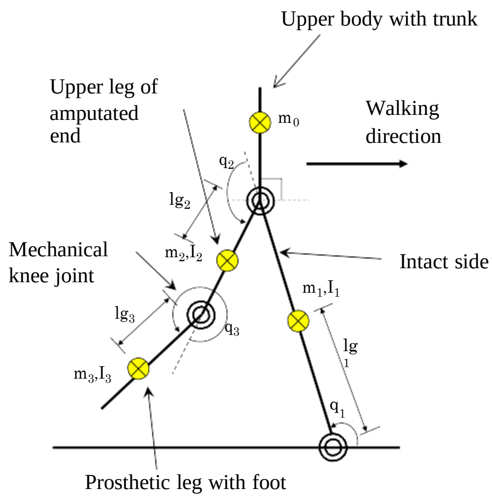


Fig. 1 Link model of prosthetic leg walking.

Dynamics of n DOF multi-body system including model in Fig.1 can be represented by the Lagrangian form in eq.(1).

$$H(\boldsymbol{q})\ddot{\boldsymbol{q}} + \frac{1}{2}\dot{H}(\boldsymbol{q})\dot{\boldsymbol{q}} + S(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{g}(\boldsymbol{q}) = \boldsymbol{\tau} \tag{1}$$

where $\boldsymbol{q} \in R^n$ denotes joint angle of the mechanism. Matrices $H(\boldsymbol{q}) = [h_{i,j}]$ and $S(\boldsymbol{q},\dot{\boldsymbol{q}})$ denote inertia matrix and skew symmetric matrix related to centrifugal and Colioris force, respectively. Vectors $\boldsymbol{g}(\boldsymbol{q})$ and τ represent gravitational force and joint torque, respectively.

B. Ineartia-Induced Measure

Now, consider to regard effective use of the inertia property as closeness of the given gait to that of inertia-induced motion. The set of all postures of the system can be regarded as Riemannian manifold [8]. A length of the trajectory connecting given two postures from $\boldsymbol{q}(a) = \boldsymbol{q}_a$ to $\boldsymbol{q}(b) = \boldsymbol{q}_b$ on the manifold can be defined as eq.(2).

$$L = \int_a^b \sqrt{\sum_{i,j=1}^{n} h_{i,j}(\boldsymbol{q})\dot{q}_i(t)\,\dot{q}_j(t)}\; dt \tag{2}$$

where component of inertia matrix $h_{i,j}(\boldsymbol{q})$ is regarded as Riemannian metric [8]. Trajectory minimizing eq.(2) is called geodesic and its length $d(\boldsymbol{q}_a, \boldsymbol{q}_b)$ given in eq.(3) is called Riemannian distance.

$$d(\boldsymbol{q}_a, \boldsymbol{q}_b) = \inf \int_a^b \sqrt{\sum_{i,j=1}^{n} h_{i,j}(\boldsymbol{q})\dot{q}_i(t)\,\dot{q}_j(t)}\; dt \tag{3}$$

Equation of geodesic obtained by solving optimization problem of eq.(3) is given by eq.(4) [8].

$$H(\boldsymbol{q})\ddot{\boldsymbol{q}} + \frac{1}{2}\dot{H}(\boldsymbol{q})\dot{\boldsymbol{q}} + S(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} = 0 \tag{4}$$

This equation coincides with dynamic equation with only inertial force but without external joint torque and gravitational force. This equation represents law of inertia of the multi-body system. Namely, trajectory from $\boldsymbol{q}_a$ to $\boldsymbol{q}_b$ by only inertial force without any external torque can be described by equation of geodesic eq.(4) and the length of eq.(2) is minimized in this case.

Sekimoto et al. have defined closeness of the movement given two points $[\boldsymbol{q}_a, \boldsymbol{q}_b]$ to the inertia-induced motion based on the Riemannian distance or the degree of inertia-induced motion as eq.(5) and have called inertia-induced measure [6].

$$R_N = \frac{L - d(\boldsymbol{q}_a, \boldsymbol{q}_b)}{d(\boldsymbol{q}_a, \boldsymbol{q}_b)} \tag{5}$$

In this paper, we attempt to apply the inertia-induced measure to characterize walking skill with the trans-femoral prosthesis.

C. Calculation Procedure of Inertia-induced Measure

In calculation of eq.(5), L is calculated from eq.(2) numerically using measured data in the experiments. The Riemannian distance $d(\boldsymbol{q}_a, \boldsymbol{q}_b)$ is calculated by solving boundary value problem associated by eq.(4) with boundary condition $\boldsymbol{q}(a) = \boldsymbol{q}_a$ and $\boldsymbol{q}_b(b) = \boldsymbol{q}_b$, then calculated by eq.(2) along the obtained trajectory, say, geodesic. Please note that the angular velocity of the start and the end of the gait cannot be specified in advance but is determined after the calculation of the boundary value problem.

Swing phase is divided into three sub phases and then the degree of inertia-induced motion in each sub phase is calculated to investigate effect of the inertia property of the prosthesis in each phase. Three phases are defined as shown in Fig.2 based on gait analysis method[9]. Phase I called Initial swing is defined as the duration from the start of the swing phase or toe off to feet adjacent. The feet adjacent is the time when the swinging leg passes the stance phase leg, and the two fee are side by side. Phase II called midswing is defined as the duration from the feet adjacent to tibia vertical. Phase III called terminal swing is defined as the duration from the tibia vertical to the end of swing phase or heel contact.

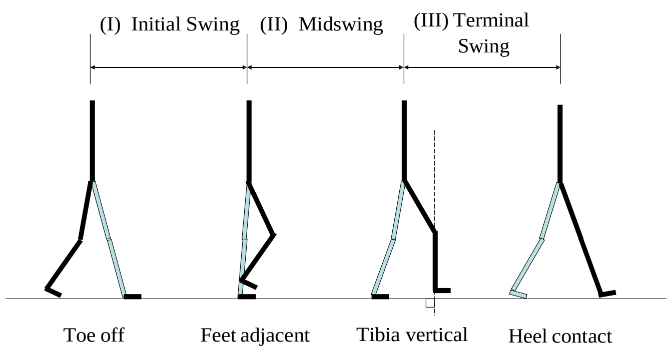


Fig. 2 Three sub-phases in swing phase

III. Experiments

A. *Experimental MethodFigures and Tables*

Fig.3 shows a participant of the experiments with a prosthesis. Fig.4 shows an experimental scene. A modular type of prosthesis leg is used in this research. A knee joint 3R106 (Otto Bock) is utilized because it is easier to add weight due to its light original weight (0.14kgf). In addition, it employs the relatively simple control method such as a simple damping control. The damping coefficient can be changed by a mechanical lever in 8 levels. A foot part 1C40 (Otto Bock) and a IRC type socket that are used in the subject's daily life is used in the experiments. A male with right thigh amputation participated in the experiments three times of 5th, 8th, and 15th months from his amputation, respectively to investigate the changes in gait. He was 47 years old when amputated. He used 3R106 knee joint after amputation to 9th month. He uses C-leg (Otto Bock) from 9th month.

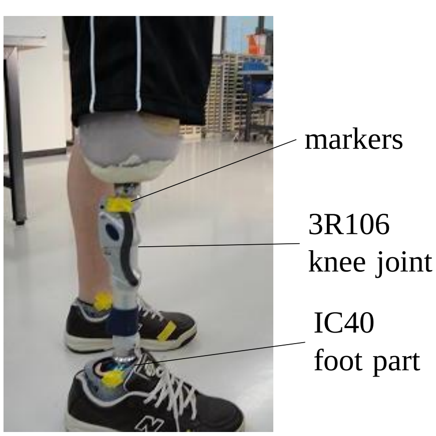


Fig. 3 Participant of experiments with prosthesis leg.

A digital camera EX-FH20 (CASIO) was set in perpendicular to the sagittal plane and recorded gaits. In the experiments, the frame rate of the camera was set as 210Hz. Markers made by color tapes attached to the hip joint of the amputated end and the knee joint, the ankle and the toe of the prosthesis and the ankle and the toe of the intact end as shown in Fig.3. Joint angles were calculated by digitizing the video images using motion analysis software DIPP-MOTION (DITECT corp.).

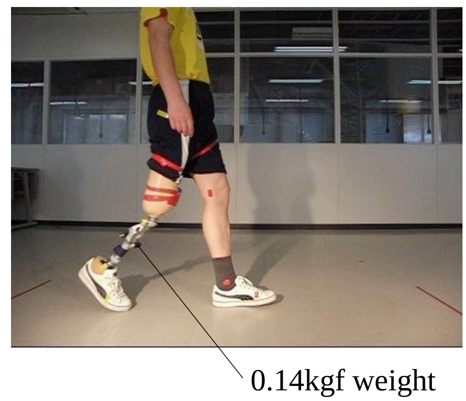


Fig. 4 Experimental Scenes.

Fig. 5 A weight attached to lower leg (0.14kgf)

There are four conditions in inertia property by adding a weight to the lower leg of the prosthesis as shown in Figs. 4 and 5 in order to investigate effect of inertia property of the prosthesis on gait. Originally, no weight is attached to the lower leg. The participant walked several times to get used to walking with the prosthesis. Then, a prosthetist and orthotist of one of the authors added a 0.14kgf weight at the lower leg of the prosthesis and the best position of the weight was determined as 48% of the length of the lower leg from the knee joint by trial and error with participant's comment at every experimental day of 5th, 8th and 15th months. The most preferable weight location is referred to as the best (weight) condition. The weight locations of the best condition for each experimental day were 52, 52, and 42%, respectively. Then, conditions 100% that means on the ankle joint and 0% that means on the knee joint were made for comparison by changing the position of the weight.

The participant was instructed to walk in the most comfortable velocity determined that is called self-select speed. The self-select speed was determined with the best weight condition. Then, the participant was asked to walk with the same walking speed even with the different weight condition. In the 15th month experiment, a metronome was utilized to indicate the self-select speed that was measured the subjective evaluation.

The trial numbers of each weight condition were three for 5th and 8th months while five trials for 15th month. In the 5th month experiments, the order of the experiment was none, 0%, best, and 100%. The participant experienced three trials of each weight condition continuously. Thus, it should be noted that the order effect was not eliminated in the 5th month experiments. In the 8th and 15th experiments, the order of the trials were randomized in weight conditions so that the order effect was eliminated. Namely, a trial was followed by another trail with the different weight condition essentially and the order was randomized. As the subjective evaluation, the participant was asked to evaluate the easiness of walk using VAS (visual analogue scale) from “difficult to walk” to “easy to walk” as shown in Fig.6. The results of the VAS evaluation will be scored as 0 (difficult to walk) to 100 (easy to walk). In the 5th month trial, the subjective evaluation was done after each weight condition while the evaluations were done after each trial in the 8th and 15th month experiments.

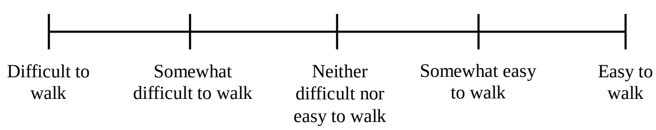


Fig. 6 VAS for subjective evaluation

B. Identification of Inertia Property of Prosthesis and Human Body

In the calculation of the inertia-induced measure in eq.(5), inertia property of the whole body including the prosthesis is required. Inertia parameters were identified based on the method in literature[5]. In the identification method, inertia parameters of the prosthesis was identified based on the direct measurement with weight scale and swinging experiments. The inertial parameters of the human body such as mass, moment of inertia, and location of center of gravity of the intact end and the other body including trunk can be calculated based on cadaver data’s proportion by Clauser [11]. As a result, the estimated inertia parameters in the model of Fig.1 calculated by the derived method are given in Table I.

TABLE I
IDENTIFIED INERTIAL PARAMETERS

Link #	Weight location%		m_i [kg]	Lg_i [m]	I_i [kgm^2]	L_i [m]
0			44.1			
1			10.5	0.519	0.659	0.840
2			5.05	0.156	0.111	0.445
3	None		1.617	0.209	0.128	0.395
	0		1.348	0.192	0.151	
	best	42		0.203	0.144	
		52		0.202	0.145	
	100			0.211	0.142	

IV. EXPERIMENTAL RESULTS

A. Subjective evaluation of easiness of walking

Fig.7 shows the transition of subjective evaluation at every experimental month. Evaluation results are not changed by prosthesis usage in the best weight condition and none weight condition. The participant rated the best condition 1st or 2nd around 80. None weight condition was rated as 50 through the experiments. The subjective evaluation of 100% weight condition is decreased by prosthesis usage. It is also found that the variation of the subjective evaluation is increased by history of prosthesis usage. This implies that accuracy of the subjective evaluation of easiness of walking is increased by the prosthesis usage.

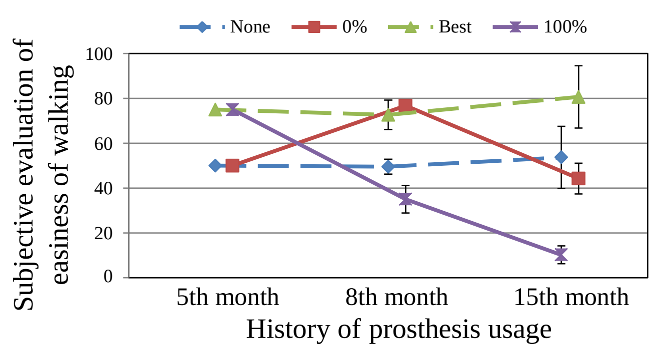


Fig. 7 Transition of inertia-induced measure in best weight condition

B. Inertia-induced measure

Fig.8 shows transition of the inertia-induced measure R_N with the best weight condition as an example. It is found that R_N of all phases decreased from 5 months to 8 months. The inertia-induced measure R_N at phase 1 increased again in 15th month while those of phases II and III are not changed. Let us consider the proportion in each month. In 5 months, all R_N takes larger values while all R_N in 8 months takes smaller values. In 15th month, R_N in the phase I takes larger values than phase II and III. This implies that the participants succeeded to decrease R_N in all phases at 8th month. In addition, the participants obtained new skill to active phase I and inertia-induced motion in phases II and III at 15th month. Deviation of the inertia-induced measure is also decreased at 8th and 15th months than 5th month.

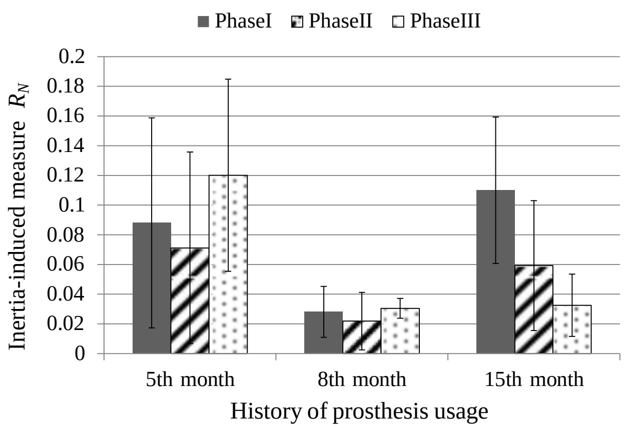
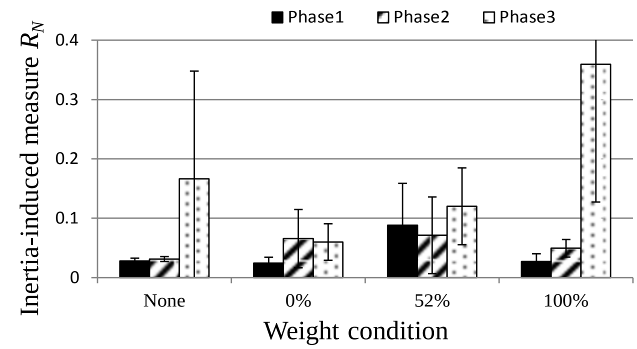
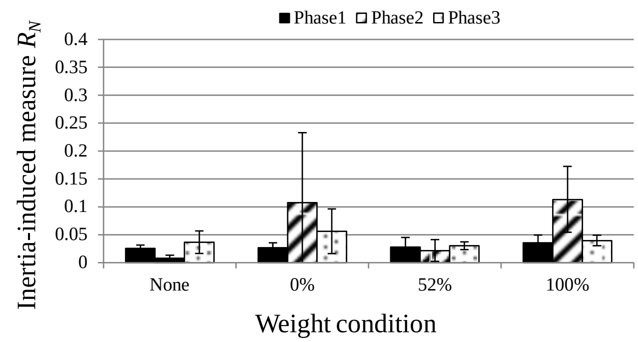


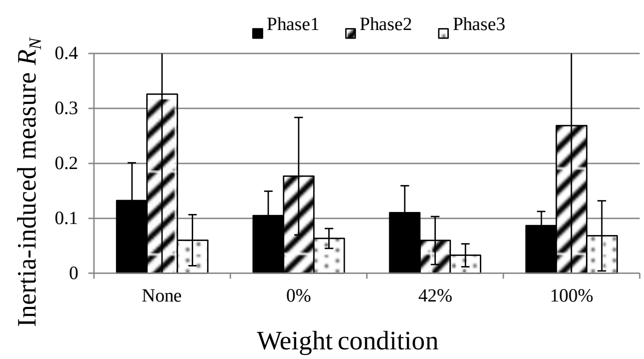
Fig. 8 Transition of inertia-induced measure in the best weight condition

Fig.9 shows the inertia-induced measure in every weight location conditions. As seen from these figures, inertia-induced measure in the 5th month changed by the weight location conditions. The inertia-induced measure in the best condition takes larger values. The subjective evaluation of easiness of walking has a positive correlation with inertia-induced measure calculated through the swing phase (R = 0.473). The inertia-induced measure at the 8th month takes relatively small values. The subjective evaluation has weak negative correlation with inertia-induced measure calculated through the swing phase (R = -0.314). The inertia-induced measure at the 15th month takes relatively constant values through the weight location conditions. There weak negative correlation between the subjective evaluation and the inertia-induced measure in phaseIII (R= -0.206).





(b) 8th month



(c) 15th month

Fig. 9 Inertia-induced measure in every weight condition

C. *Comparison of knee joint angles*

Fig.10 shows joint time series pattern of the prosthesis knee joint at every months with the best condition. The maximum flexion angle of the knee joint at 15th month is much larger than those at 5th and 8th months. In addition, larger flexion of the knee joint leads to later extension of the knee joint.

From these observations, it is understood that the usage of the inertia-induced motion is changed according to the walking skill with the trans-femoral prosthesis.

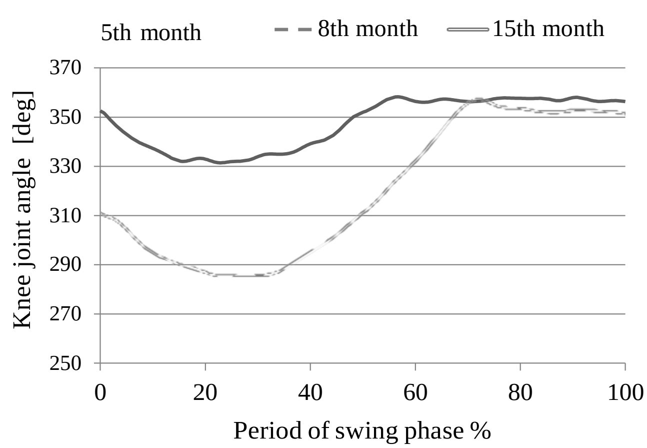


Fig. 10 Transition of inertia-induced measure in best weight condition

V. Conclusion

Changes of inertia-induced measure, gait, and subjective evaluation of easiness of walking by the history of prosthesis usage with the trans-femoral prosthesis have been investigated in order to investigate effect of the walking skill. From the analysis results, it is found that the inertia-induced measure is decreased at the 8th month through the swing phase. Then, the measure in the phase I is increased while the measure in the phases II and III is decreased. This implies that the active step at the beginning of the swing phase followed by the inertia-induced motion can be obtained at the third level of the prosthesis walking. This is led by the larger maximum knee flexion angle of the prosthesis that might increase dynamic walking and walking velocity. This implies that the walking skill with the prosthesis can be identified by specific patterns of inertia-induced motion in each sub-phase in the swing phase and gait pattern including knee joint angle of the prosthesis. This result could be utilized for evaluation of inertia matching of the prosthesis to the given user. In addition, the accuracy of the subjective evaluation is increased by the history of the prosthesis usage.

As a future study, a method to increase time resolution of the inertia-induced measure will be developed. In addition, a rehabilitation method that is based on the results of this paper will be developed as an important future research studies.

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