Evaluation of Gait with Trans-Femoral Prosthesis based on Riemannian Distance

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***Abstract* - This paper presents a method to quantify the goodness of gait with a trans-femoral prosthesis in order to evaluate walking skill with the prosthesis and its application to its design. Advancements in the mechanism and the control method of trans-femoral prostheses have drastically improved the gait of amputees. However, realization of a natural gait has not been investigated in detail even though such smooth gait is important to increase the amputee's activities of daily living (ADL). Inertia of the prosthesis plays an important role in natural and smooth gaits during the swing phase. We suppose that goodness of gait or easiness of walking is strongly related to effective use of the prosthesis inertia. Recently, inertia-induced measure has been proposed as a measure to quantify inertia-induced motion of a multi-body system based on the Riemannian distance. In this paper, we will attempt to evaluate the goodness or easiness of walking with a prosthesis leg by quantifying the effective use of the prosthesis inertia based on the Riemannian distance. Gaits with several different inertia properties will be measured. The results will then demonstrate the strong relevance between subjective evaluation of easiness of walking and effective use of inertia evaluated based on the Riemannian distance.**

Index Terms - Prosthesis leg, Easiness of walking, Riemannian distance, Iinertia-induced Measure, Inertia-induced Motion.

I. INTRODUCTION

Prosthesis legs are necessary for amputees to realize locomotion in their daily lives. People whose leg was amputated above the knee use a trans-femoral prosthesis that has a mechanical knee joint. In such a prosthesis, mechanism and control method are important to guarantee safe locomotion. For instance, flexion of the knee should be prevented in the stance phase of walking, but the knee needs appropriate flexion in the swing phase to prevent stumbling and falling. From such a viewpoint, much research and development has been conducted on the knee flexion mechanism and control method to determine appropriate timing of heel contact on the floor. In particular, computer-controlled trans-femoral prostheses developed in recent years significantly contribute to dramatically increasing safety in walking with a prosthesis [1], [2], [3].

The swing phase is important for realizing a smooth gait and easiness of walking with the prosthesis, and such goodness of gait is important for increasing the amputee’s activities of daily living (ADL). Computer-controlled prostheses increase gait smoothness in the swing phase by employing state-of-the-art control techniques and mechanisms [2], [3]. Few researchers, however, have dealt with defining or quantifying the easiness of walking. Gait smoothness in the swing phase can be strongly affected by inertia and the control method of the prosthesis. It has been thought that a light-weight prosthesis is preferable because it can avoid large disturbances in gait on muscular load. However, we believe that the appropriate inertia is important for realizing a smooth and comfortable gait. In fact, our experiments demonstrated that an amputee feels comfortable walking with a prosthesis of moderate inertia, possibly because the load is decreased by skillfully utilizing the prosthesis inertia. Therefore, this research aims at quantifying the goodness of gait or easiness of walking from the viewpoint of effective use of the prosthesis inertia.

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 easiness of walking from the viewpoint of dynamics are not found even though such an approach is important for applying the results to design methodology of prostheses.

On the other hand, very recently, Arimoto et al. have shown that given a multi-joint robot, the set of all its postures can be regarded as a Riemannian manifold by composing the Riemannian metric of its inertia tensor. Based on this, they have proven the stability of position and force hybrid control of redundant robotic systems under holonomic constraints by means of the Riemannian distance in the constraint submanifold [5]. Sekimoto et al. have shown that a geodesic connecting any two postures in the Riemannian manifold, which relates to the Riemannian distance, represents inertia-induced motion of multi-body robotic systems in a physical sense. In addition, they have applied the concept to natural motion planning of multi-joint robotic systems using inertia-induced effects [6]. Furthermore, Sekimoto et al. have proposed an inertia-induced measure that evaluates the closeness of the given motion to the inertia-induced motion based on the Riemannian distance and successfully applied it to analysis of skill in reaching movement of human arm [7]. In this research, we will evaluate smoothness of gait in the swing phase of prosthetic leg walking based on the Riemannian distance. Namely, we propose a method to evaluate the goodness of gait in prosthetic leg walking from the viewpoint of skill in utilizing inertia.

In this paper, gait with a trans-femoral prosthesis is measured by changing its inertia. The relationship between subjective evaluations of easiness of walking for each inertia condition and effective use of prosthesis inertia based on the Riemannian distance is then investigated. The experimental results will show possibility of evaluating walking easiness by the inertia-induced measure.

II. EXPERIMENTS

A. Experimental Method

Fig.1 shows a participant of the experiments with a prosthesis. Fig.2 shows experimental scenes. A modular type of prosthesis leg is used in this research. A knee joint 3R95 (Otto Bock) is utilized because it is easier to add weight due to its light original weight (0.35kg). 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 of 45 years old with left thigh amputation participated in the experiments. He uses the prosthetic leg for 11 years in his daily living. He uses C-Leg (Otto Bock) as the knee joint of the prosthesis daily.

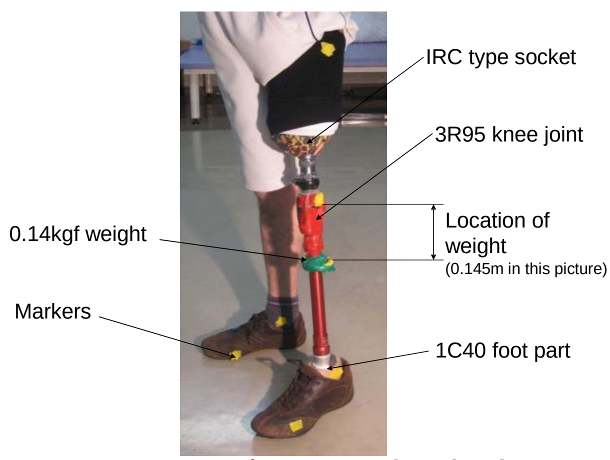


Fig. 1 Participant of experiments with prosthesis leg.

Fig. 2 Experimental Scenes.

Table 1 shows experimental conditions in inertia and walking velocity. There are four conditions in inertia property by adding weight to the lower leg of the prosthesis as shown in Fig.1 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 0.140kgf weight at the lower leg of the prosthesis and the best position of the weight was determined as (B) 0.145m from the knee joint by trial and error with participant's comment. Then, conditions (C) and (D) were made for comparison by changing the position of the weight.

A digital camera EX-F1 (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 colour 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.1. Joint angles were calculated by digitizing the video images using motion analysis software DIPP-MOTION (DITECT corp.).

The participant was instructed to walk in his normal speed. In addition, he was asked to walk in slower and faster velocities in order to investigate effect of walking velocity on gait and inertia induced motion. In the experiments, resultant mean durations of swing phase in slow, normal, and fast conditions were 0.49s (SD 0.045), 0.44s (SD 0.022), and 0.40s (SD 0.019), respectively. The numbers from 1 though 12 in Table I denote the order of the experiment for each condition.

TABLE I
EXPERIMENTAL CONDITIONS

		Walking velocity		
		Normal	Slow	fast
Location of additional weight from knee joint [m]	(A) None	1	2	3
	(B) 0.145	4	5	6
	(C) 0.3	7	8	9
	(D) 0	10	11	12

B. Identification of Inertia Property of Prosthesis and Human Body

A modular type of the artificial leg is used as mentioned before. So, the thigh, the lower leg, and the foot module can be separated and the parameters of each part are identified separately. Mass of each part is measured by an electronic balance. Assume that the center-of-gravity of each part is located on the line connecting two joints on the link. Thus, the center of gravity is measured from equilibrium of moment using the electronic balance and a lever. The moment of inertia is measured by hanging it at the one end and by measuring frequency of vibration by swinging the part as a pendulum.

On the other hand, inertia of the human body is calculated as follows. Inertial parameters 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 [9]. In addition, inertia parameters of the upper leg in the amputated end are similarly estimated based on the Clauser's method. Assume that shape of the upper leg can be approximated by circular truncated cone as shown in Figs.3 and 4 where l_{amp} and l_{int} denote length of amputated end and that of upper leg of the intact end. Radii r, r_{amp}, and r_{int} are calculated by measuring perimeters of each part. Then, volume of the upper leg of the amputated end is estimated as the volume of the circular truncated cone. Mass, location of center of gravity, and moment of inertia can be estimated by assuming density of upper leg is constant and using Clauser's proportion.

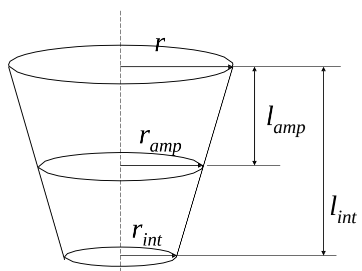


Fig. 3 Approximated shape of upper leg.

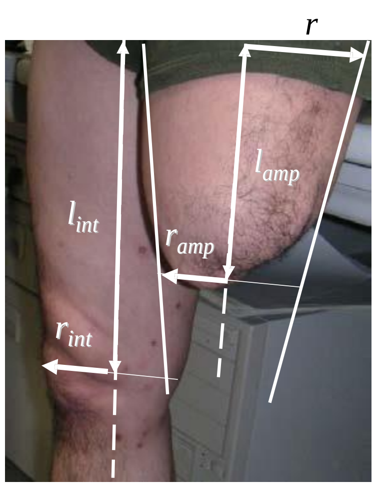


Fig. 4 Dimension of amputated end.

Motion in the swing phase with the prosthesis is modeled by Fig.5. 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. The estimated inertia parameters of the Fig.5 calculated by the derived method are given in Table 2.

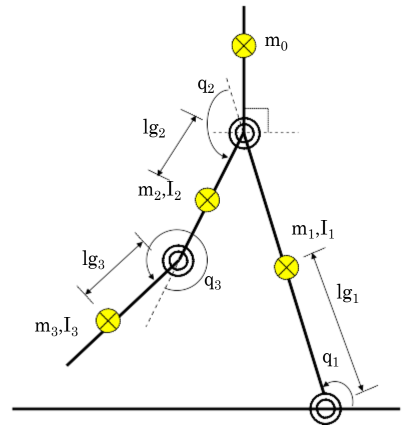


Fig. 5 Four link model of prosthetic leg walking.

TABLE II
ESTIMATED INERTIAL PARAMETERS

Link #	Weight location	m_i [kg]	Lg_i [m]	I_i [kgm^2]	L_i [m]
0		43.905			
1		9.150	0.422	0.701	0.78
2		5.370	0.132	0.680	0.38
3	None	1.208	0.234	0.0163	0.40
	0	1.348	0.210	0.0231	
	0.145		0.225	0.0173	
	0.3		0.241	0.0168	

III. INDEX OF INERTIA-INDUCED MOTION BASED ON RIEMANNIAN DISTANCE FOR QUANTIFYING SMOOTHNESS OF GAIT

Let us consider to quantify smoothness of gait based on effective use of the prosthesis inertia. Now, the motion derived by inertial force is formulated. Dynamics of n DOF multi-body system including model in Fig.4 can be represented by the Lagrangian form in eq.(1).

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

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 external joint torque, respectively. Now, consider to represent smoothness of motion governed by dynamics eq.(1) in a viewpoint of effective use of inertia property.

The set of all postures of the system can be regarded as Riemannian manifold [10]. 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).

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

where component of inertia matrix $h_{i,j}(\boldsymbol{q})$ is regarded as Riemannian metric [11]. Trajectory minimizing eq.(2) is called geodesic and its length $R_d(\boldsymbol{q}_a, \boldsymbol{q}_b)$ given in eq.(3) is called Riemannian distance.

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

Equation of geodesic obtained by solving optimization problem of eq.(3) is given by eq.(4) [5].

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

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 as eq.(5) and have called inertia-induced measure [8].

$$\overline{\Delta R} = \frac{L(\boldsymbol{q}) - R_d(\boldsymbol{q}_a, \boldsymbol{q}_b)}{R_d(\boldsymbol{q}_a, \boldsymbol{q}_b)} \tag{5}$$

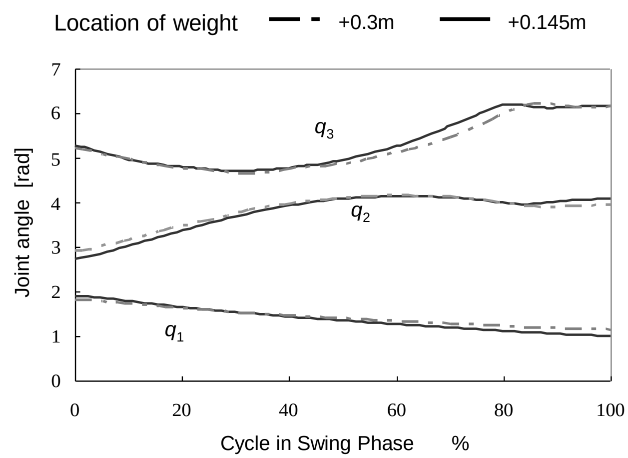
Sekimoto et al. have successfully analyzed skillfulness of reaching movement of human arm using this measure [8].

In this paper, we regard eq.(5) as quantity of effective use of inertia property, thus, examine whether the index can represent goodness of gait with prosthesis.

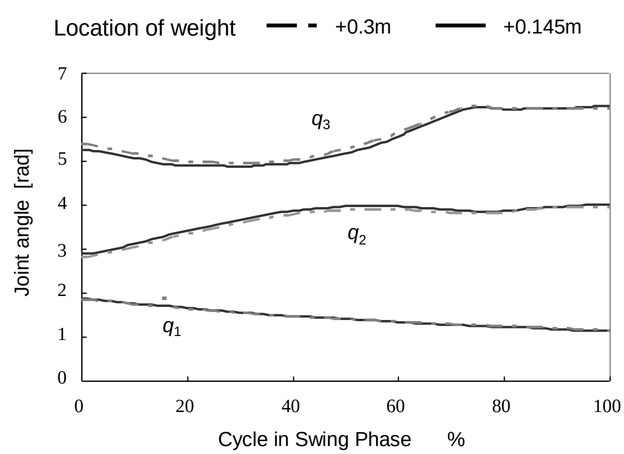
In calculation of eq.(5), $L(\boldsymbol{q})$ is calculated from eq.(2) numerically using measured data in the experiments. The Riemannian distance $R_d(\boldsymbol{q}_a, \boldsymbol{q}_b)$ is calculated by solving boundary value problem associated by eq.(4) with boundary condition $\boldsymbol{q}(a) = \boldsymbol{q}_a$ and $\boldsymbol{q}_b(b) = \boldsymbol{q}_b$, then calculated by eq.(2) along the obtained trajectory, say, geodesic.

IV. Experimental Results

Fig.6 shows examples of joint angles in the swing phase measured in fast and normal walking velocity conditions. Results of 0.145m weight location condition that obtained the best subjective evaluation and 0.3m conditions with the worst subjective evaluation are plotted in these figures. The horizontal axis represents time normalized by the duration of the swing phase. In the fast walking condition, phase of knee angle of the prosthesis q_3 in 0.145m condition is faster than 0.3m condition. This coincides with our knowledge based on law of inertia. In addition, this could be corresponding to the comment of the participants that he felt the prosthesis heavy and felt fear for late heel contact. On the other hand, there is no clear tendency to be explained in joint angles q_1 and q_2. In the normal walking condition, high repeatability can be found in q_1. Amplitude of knee flexion q_3 in 0.3m condition is smaller than that in 0.45m condition. Similarly, extension of the hip joint angle q_2 in 0.3m condition is smaller than that in 0.45m condition even though the difference is small.



(a) Fast walking condition



(b) Normal walking condition

Fig. 6 Inertia-induced Measure vs weight location and walking velocity.

Fig.7 shows relationship between inertia-induced measure and location of the weight and the walking velocity. Obviously, inertia-induced measure in slower walking velocity is significantly larger than the other velocity conditions. This can be understood that effect of gravitational force that is ignored in the inertia-induced measure is larger in slower condition. This implies that the inertia-induced measure can be more effective in relatively faster situation. In addition, the inertia-induced measure becomes the smallest in 0.145m condition with the best subjective evaluation for each walking velocity. Furthermore, the measure takes its smallest value in normal walking velocity with 0.145 weight location. These mean that inertia-induced measure is small when the easiness/comfort of walking is high. It should be noted that no significant change can be found in 0.3 and 0.145 conditions in fast velocity. This implies that inertia-induced measure is sensitive in normal velocity that is strongly related to comfortable walking. Inversely, it might be hard to extract differences between these conditions due to slight differences in the fast condition.

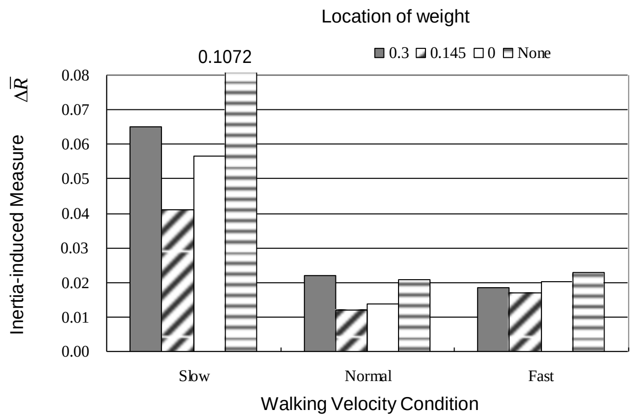


Fig. 7 Inertia-induced Measure vs weight location and walking velocity.

Fig.8 shows relationship between prosthesis lower leg's moment of inertia around the knee joint and the inertia-induced measure. As seen from these figures, 0.145m condition with the best subjective evaluation has the middle value in moment of inertia. In the normal walking condition, clear tendency can be found between the moment of inertia and the inertia-induced measure. Some scattering in inertia-induced measure is found even in the same moment of inertia in slower conditions. This implies that the other factor affects inertia-induced measure. Especially in slow condition, mass itself would affect the measure.

V. Conclusions

Relationship between the inertia-induced measure and the subjective easiness of walking with the trans-femoral prosthesis has been investigated in order to quantify the goodness or comfort of gait with the prosthesis from the view point of effective use of its inertia. As the results, it has been shown that inertia-induced measure becomes smaller when using the prosthesis that has moderate inertia with high subjective evaluation in the easiness of walking. This shows possibility that gait close to the inertia-induced motion is appeared in the comfortable walking. In addition, it is found that the inertia-induced measure was strongly affected by gait velocity, that is, inertia-induced measure becomes larger in slow walking velocity. It would be affected by gravitational force that is not taken into consideration in the measure. Furthermore, it has been shown that there exists an extent of inertia that can be utilized easily from the results of relationship between inertia-induced measure and moment of inertia of the prosthesis lower leg around the knee joint. Consequently, the possibility that the easiness / comfort of walking with the given prosthesis is evaluated by the inertia-induced measure has been shown.

In this paper, overall gait in swing phase was evaluated by the measure. As a future work, effective use of inertia will be analyzed in detail by dividing the swing phase in several phases. This will show the skillfulness of walking, that is, when inertia-induced motion is utilized and when human controls its motion actively.

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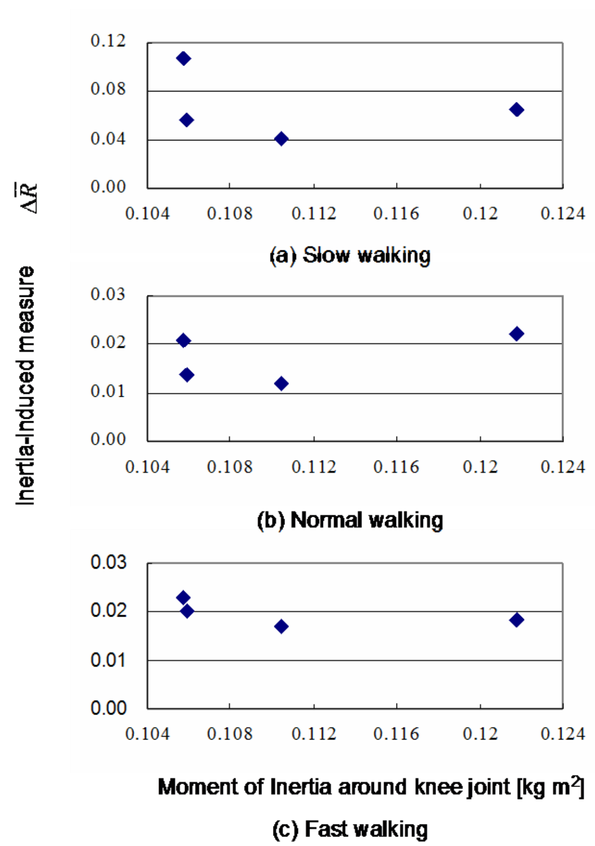

Fig. 8 Moment of inertia around knee joint vs Inertia-induced Measure.

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