Basic Research on Power Limb Using Gait Information of Able-Side Leg

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Abstract: The paper describes a novel walking support system for the aged, disabled and persons who have difficulty in walking. The walking support system in this paper refers to not only artificial leg and prosthesis but power suit with actuators to assist the user in locomotion. The mathematical model of walking support system is derived from the simplified inverted pendulum. The behavior of walking support machines must be simple for users. On the other hand, The user should be able to manipulate the walking support machine easily. Therefore, we propose a strategy using hip and knee angles to estimate the next step states which are important values for a walk support system. Also those angles are useful information that we can get easily. In this paper, we intend to introduce a concept of walking support system and a fundamental strategy of walking support using gait information of able-side leg. Simulation results and experimental results will be presented to show the effectiveness of the proposed system.

1 INTRODUCTION

Conventional above knee prostheses without any actuators have fixed mechanical characteristics which cannot be changed. Therefore their gait pattern is constrained to a few types. To realize various types of gaits, powered above knee prosthesis (power limb) is extremely useful[4]. In particular power limb works effectively on slopes or stairs, where conventional prostheses are not able to support the body when the legs are bent.

To realize effective walking with power limb, there is a problem that we have to solve with respect to the gait strategy. The problem is the control method for gait dynamic stability. In general, human walking model can be reduced to the simple mathematical inverted pendulum. There are several papers that dealt with the inverted pendulum for dynamic stability of biped locomotion [1]-[3][5][6]. In this paper, we pay attention to the one legged person's gait. Walking model using artificial leg is a peculiar model case with respect to gait stability method. A novel gait control system using gait information of able-side leg is proposed. Its effectiveness is shown by some simulations and experimentations. In addition, we introduce a powered above-knee prosthesis which we are making for the applications of the gait control.

2 CONCEPT OF WALKING SUPPORT SYSTEM

The gait strategy of a walking support system is based on estimation of the next step's leg-length and angle in the sagittal plane [2][3]. In Fig.1, the power limb estimates the initial motion of the next step just after the other leg touches down.
We assume that the step time interval of power limb is equal to that of the able-side leg in the previous step. This means that the walking step is taken at regular intervals.

Also by assuming that leg mass is negligible compared to body mass, the man-and-power-limb system can be considered to be an inverted pendulum with a moving support point. Fig.2 shows the walking model which is like inverted pendulum. In Fig.2, the inputs of the walking model are hip torque τ and knee bend/stretch force F. The outputs are the vertical angle of the body ϕ_2 and that of the leg ϕ_1. The body is a rigid body with mass m and inertia moment J. The motion equations of the system in Fig. 2 are as follows.

$$\begin{aligned}
&\ddot{r} + l\sin(\phi_1-\phi_2)\ddot{\phi_2} + g\cos(\phi_1) \\
&\quad -r\dot{\phi_1}^2 - l\cos(\phi_1-\phi_2)\dot{\phi_2}^2 = \tfrac{F}{m} \qquad (1)
\end{aligned}$$

$$\begin{aligned}
&r^2\ddot{\phi_1} + l\cos(\phi_1-\phi_2)r\ddot{\phi_2} - gr\sin(\phi_1) \\
&\quad +rl\sin(\phi_1-\phi_2)\dot{\phi_2}^2 + 2r\dot{r}\dot{\phi_1} = -\tfrac{\tau}{m} \qquad (2)
\end{aligned}$$

$$\begin{aligned}
&l\sin(\phi_1-\phi_2)\ddot{r} + rl\cos(\phi_1-\phi_2)\ddot{\phi_1} \\
&\quad +(l^2+\frac{J}{m})\ddot{\phi_2} + gl\sin(\phi_2) = \tfrac{\tau}{m} \qquad (3)
\end{aligned}$$

We can design the estimation system of the initial motion of the next step expressed by the following equation (4). This is obtained by linearization, decoupling control of (1), (2) and (3) and digitization.

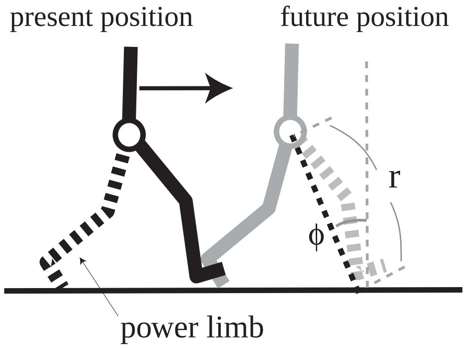

Fig. 1: Basic concept of power limb.

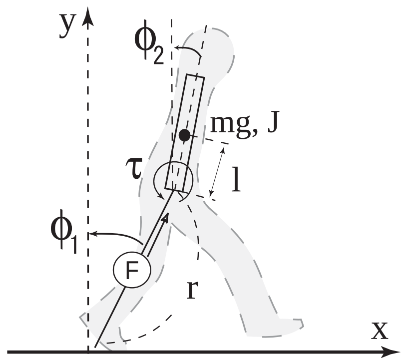

Fig. 2: Configuration of walking model.

$$\phi_D[k+1] = \begin{bmatrix} \cosh bT & \frac{1}{b}\sinh bT \\ b\sinh bT & \cosh bT \end{bmatrix} \phi_D[k] \tag{4}$$

Where $b = \sqrt{\frac{g}{r+l}}$, T is the walking step time interval, $\phi_D[k](= [\phi_1(kt), \dot{\phi}_1(kt)])$ are the discrete-time states of the able-side leg at the time when the able-side leg touches down, hence $\phi_D[k+1]$ denotes the future state after the time interval T. Then, we define the next step position (ϕ_{est}, r_{est}) in terms of u_D. u_D is derived from the state feedback theory with nominal angle ϕ_r and nominal speed v_0. ϕ_{end} denotes ϕ_1 of the disabled-side leg at the time when the able-side leg touches down.

$$u_D = h_3(\phi_{end} - \frac{\phi_r}{2}) + h_4(\dot{\phi}_{end} - \frac{v_0}{r}) + \phi_r \tag{5}$$

$$\begin{aligned} h_3 &= 1 - \lambda_3\lambda_4 \\ h_4 &= [(1+\lambda_3\lambda_4)\cosh bT - \lambda_3 - \lambda_4]/(b\sinh bT) \end{aligned} \tag{6}$$

And then, the estimated values are

$$\phi_{est} = \phi_{end} - u_D \tag{7}$$

$$r_{est} = r_{end}\cos\phi_{end}/\cos\phi_{est} \tag{8}$$

$$\dot{\phi}_{est} = \frac{\dot{r}_{end}}{r_{est}}\sin u_D + \frac{r_{end}}{r_{est}}\dot{\phi}_{end}\cos u_D \tag{9}$$

This gait control system is stable if equation (4) with feedback u_D has its all poles (λ_3, λ_4) within the unit circle. The poles are decided such that the motion of the

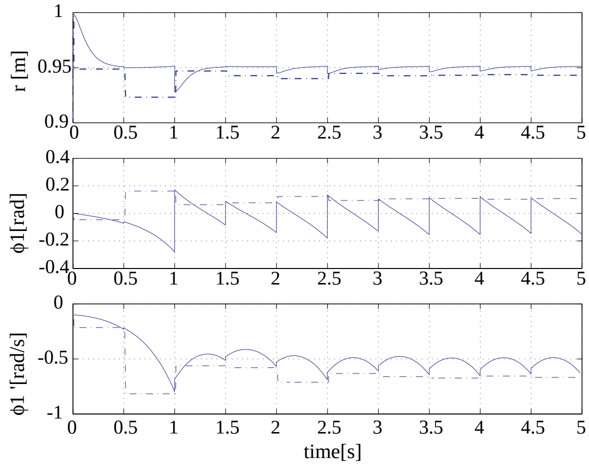

Fig. 3: Walking simulation result

power limb matches users' preferences. The gait control simulation results are shown in Figs.3-5, where in Fig. 3 the dashed lines are estimated values $(r_{est}, \phi_{est}, \dot{\phi}_{est})$ of each state and the solid lines are the reference values, Figs. 4 and 5 show the stick figures referring the simulation results. In Fig.5 the object of walking model is to climb a slope.

3 DECISION MODEL of WALKING PARAMETERS

For walking by power limb, important input parameters are the desired walking speed $v_0(= r\dot{\phi}_r)$, the desired total leg angle ϕ_r, and the desired step time interval T. Another important parameter is the desired leg length r_{ref}. In this section the r_{ref} is, however, ignored. We call these parameters (v_0, ϕ_r, T) walking parameters.

Walking parameters are not independent of each other. Intuitively we can imagine that rapid walk is not achievable if the step length is too short, and slow walk is impossible if the step length is too long. We will give a suggestion for the method of determination of walking parameters for power limb.

In general, biped robots can use the torque of hip and ankle joint actively [8]. Hence, they can actualize various gaits. However, the control is usually too complex, and the walking is not economical in terms of energy loss. The inverted pendulum algorithm that we optimize for power limb is a simple gait control to manage the walking without ankle torque.

We assume that the ankle of the power limb is not actuated in stance phase. In steady state walking, therefore, the start value $(*_{st})$ of vertical angle speed $\dot{\phi}_1$(see Fig.2) becomes equal to the end value$(*_{end})$. It is shown as

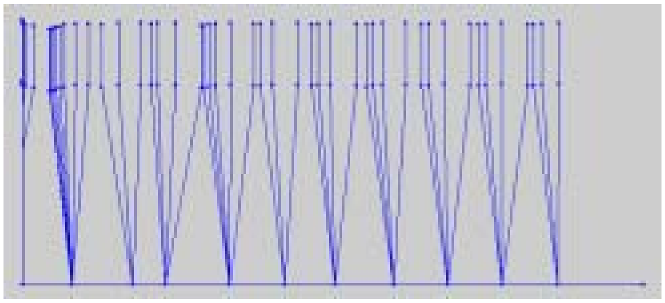

Fig. 4: Stick figure of walking model on level surface

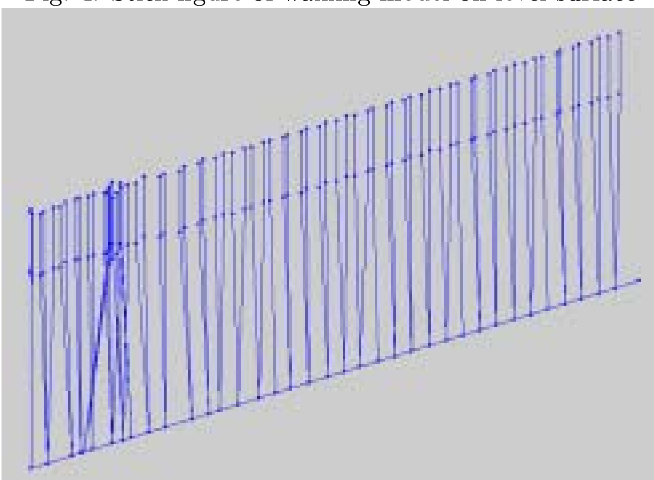

Fig. 5: Stick figure of walking model on slope

follows.

$$\dot{\phi}_{end} = \frac{b \sinh bT}{1 - \cosh bT} \phi_{start} \rightarrow \dot{\phi}_r \qquad (10)$$

By assuming that ϕ_{start} approaches to $\phi_r/2$ as the gait stabilization, the correlation function of walking parameters is given by the following equation (11).

$$\dot{\phi}_{end} = \frac{v_0}{r} = \frac{b \sinh bT}{2(1 - \cosh bT)} \phi_r \qquad (11)$$

The comparison between the reference inputs and simulation results is shown in Fig. 6. The walking simulations are performed for time intervals $T = 1.0, 0.5, 0.3$[s]. In this figure solid lines are simulation results, and dashed lines are reference inputs using equation (11). We can see that the error increases if ϕ_r becomes longer. Nevertheless, equation (11) is useful to determine the walking parameters for a large range of walking speeds.

4 ACTUAL WALKING ANALYSIS

4.1 EQUIPMENT

For actual walking analysis we use four rotary encoders in both sides of hip joint and knee joint (see Fig.7) and, two foot switches which prove whether stance phase or swing phase (see Fig.8).

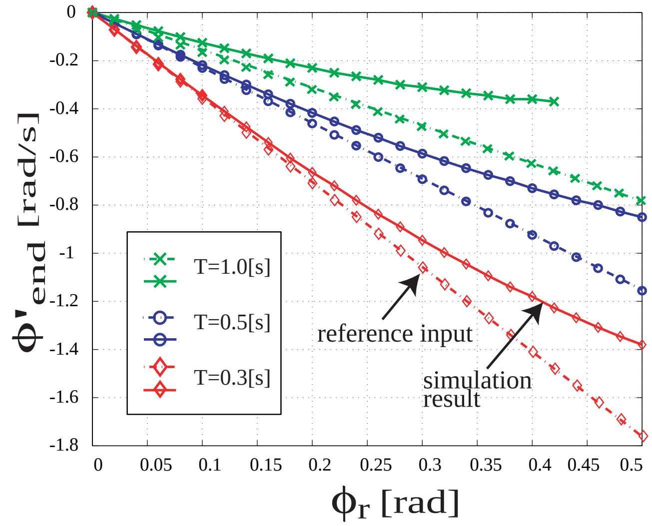

Fig. 6: Comparison of the reference inputs with decision model (eqn(11)) and simulation results for time interval T= 1.0, 0.5, 0.3 [s].

Of course hip joint has 3 degree of freedom (sagittal axis, frontal axis, horizontal axis), but we use only sagittal axis to analyse the sagittal plane motions of walking in this work. In addition, we assume that the vertical angle of the body ϕ_2 (see Fig.2) keeps zero in walking.

4.2 EXPERIMENTAL ANALYSIS

In this section, we verify that the mathematical walking model and the estimation system are valid. The walking experiment is performed on level ground for 10 seconds. The results are shown in Fig.9. In this paper, we name the disabled-side leg A-side leg and the able-side leg B-side leg. A-side leg is compared with the results from gait estimation system and B-side leg is applied to get the informations of gait motions. Fig.10 shows the transformation results of the joint angles in Fig.9. The transformation in Fig.10 is necessary for the walking model. When B-side foot changes in swing phase state, the estimate controller begins to count step time interval T, total leg angle ϕ_r and leg length r.
In particular, step time interval T and total leg angle ϕ_r show interesting characteristics. That is, T and ϕ_r in general walking motion are equal to that in the previous step. Fig.11 show the transitions of time interval T of A-side and B-side leg, Fig.12 shows the transition of leg angle ϕ_r by B-side leg. Because those transitions are small, the foregoing simulation assumption is quite adequate.
Next, the proposal estimation system applies to actual walking and walking model. The results are showed in Fig.13, 14, which the solid lines are the walking results, and the dashed lines are estimated values

Fig. 7: The illustration of equipped with instrument system.

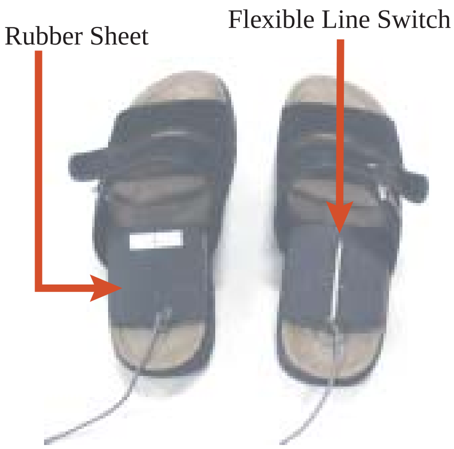

Fig. 8: The illustration of touch sensors.

$(r_{est}, \phi_{est}, \dot{\phi}_{est})$ of each state.
In the simulation result (in Fig.14), walking parameters (v_0, ϕ_r, T) and the desired step r_{ref} are fixed beforehand with the result of the actual walking, and in the actual walking result (in Fig.13) the step time interval T is obtained when B-side foot touches down. The other parameters are being calculated from $T/2$ until A-side foot touches down, because the estimation of actual walking can't be determined at the beginning of B-side foot stance phase. There is a difference in the way of touching down between the walking model and actual walking, which is that $\dot{\phi}_1$ fluctuates significantly at the beginning of stance phase (see Fig.16).
On the whole, we can say that these results demonstrate that the model can be applied to the powered artificial leg sufficiently. Fig.15, 16 show the phase diagram in $\phi_1, \dot{\phi}_1$ of actual walking.

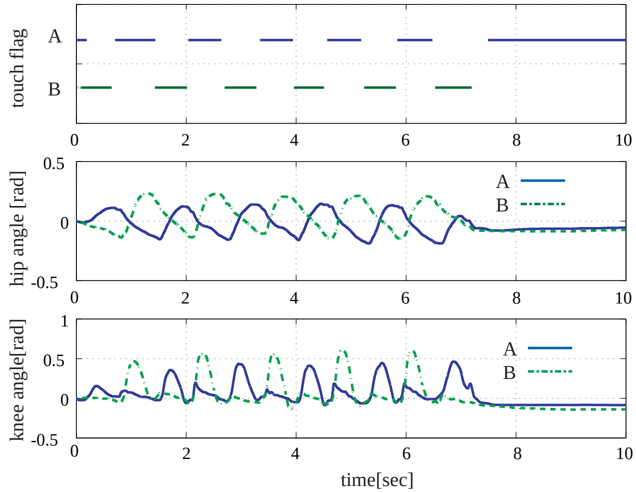

Fig. 9: Hip and knee joints motion results.

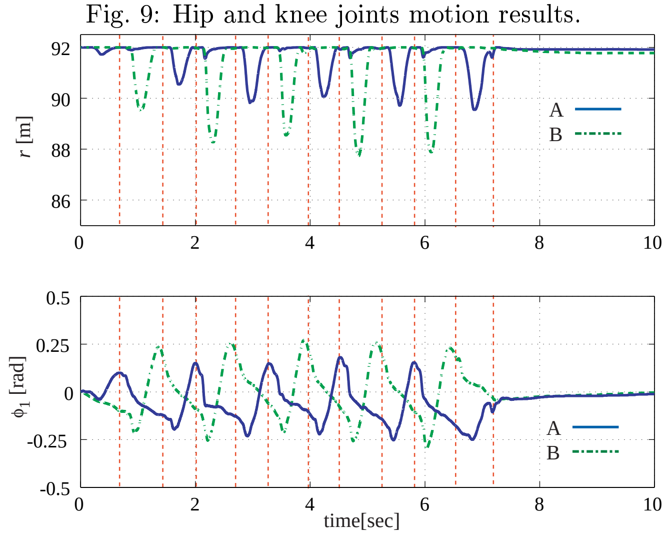

Fig. 10: Data processing results with hip and knee joint motion data.

5 EXPERIMENTAL APPARATUS

At the time of writing, we have made the powered above-knee prosthesis to verify the proposal, and are establishing the joint motion control system. Essentially, total power limb with hip and knee joints should be made for the proposal, but as a starter the power limb with only knee joint has been made. Some data with respect to the experimental apparatus are shown in following charts. The image of the apparatus is shown in Fig. 17, and that of the drive unit is in shown Fig. 18. The apparatus has an actuator at the knee joint which is an AC 0.4 [kW] motor and a foot switch at the end of the leg (see Fig.17). We intend to research the usability and the performance of the proposed estimation system. In general actuators for human leg should be light weight. The reason of the use for AC motor is that the electric motor can be made to simulate the behavior of various actuators commonly used to power limb through appropriate control.

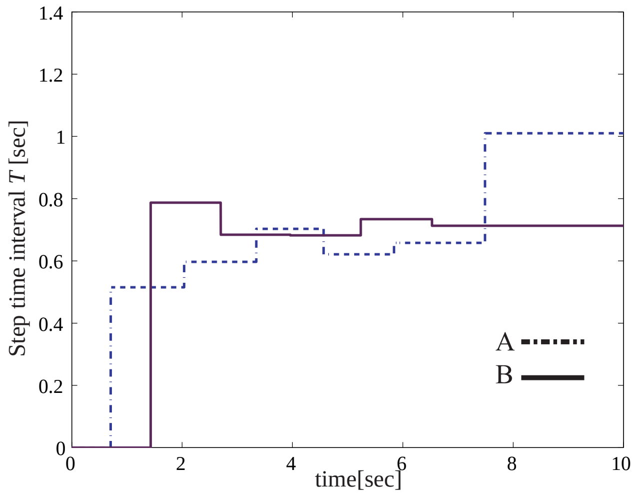

Fig. 11: Step time interval T oscillation result.

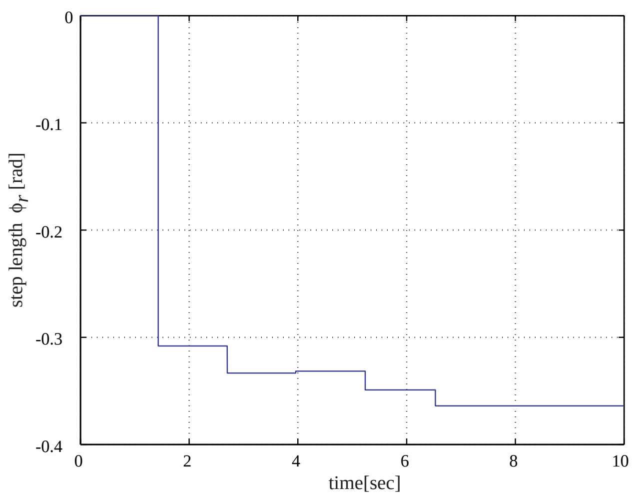

Fig. 12: Total leg angle ϕ_r oscillation result.

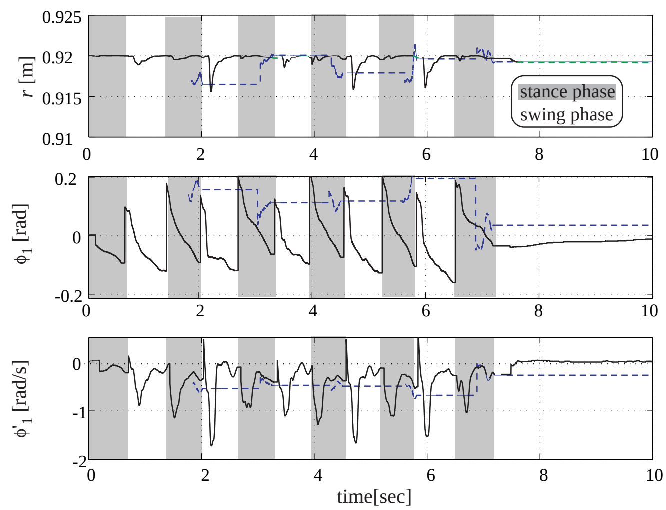

Fig. 13: Actual walking results.

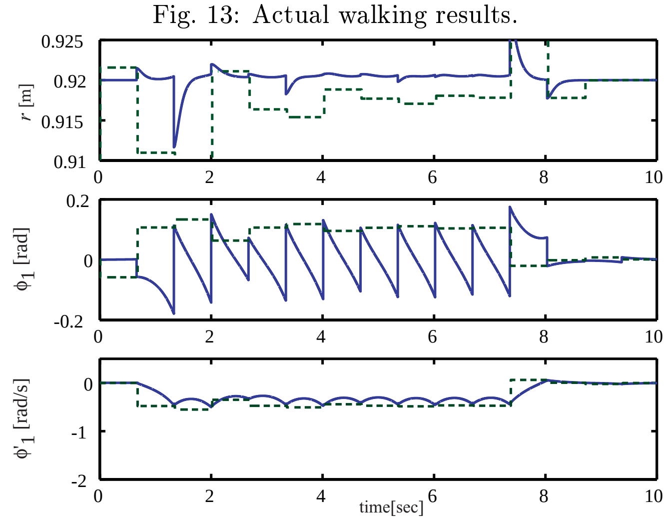

Fig. 14: Simulation results of walking model.

(a) drive system data

parameter	data
motor	Fuji Electric Co., Ltd GYC401DC1-S (AC motor)
mass	1.9 [kg]
normal power	0.4 [kW] 1.27 [Nm]
max torque	3.82 [Nm]
max rotary speed	5000 [rpm]
inertia moment	0.0412×10^{-3} [kgm^2]
speed reducer	strain wave gear
reduction ratio	80

(b) body frame data

parameter	data
width × thin × height	218, 115, 500 [mm]
mass	5.2 [kg]

(c) instrumentation data

parameter	data
control system	CPU: Athlon 400 [MHz] OS: ART-Linux

6 CONCLUSION and FUTURE WORK

In this paper, we proposed a novel gait control method for walking support system, especially for above-knee prostheses, and compared our gait control method with actual human gait through experiment. We then introduced our power limb experimental set-up for the implementation of our proposal. At present, we are analysing walking on slope and steps using the walking model, and making an expert system to establish an fail-safe walking support system.

In the near future, difficulty in walking will become a serious problem in aging societies like Japan and other advanced countries. Our works are concerning gait control methods for power limbs, but our main purpose is

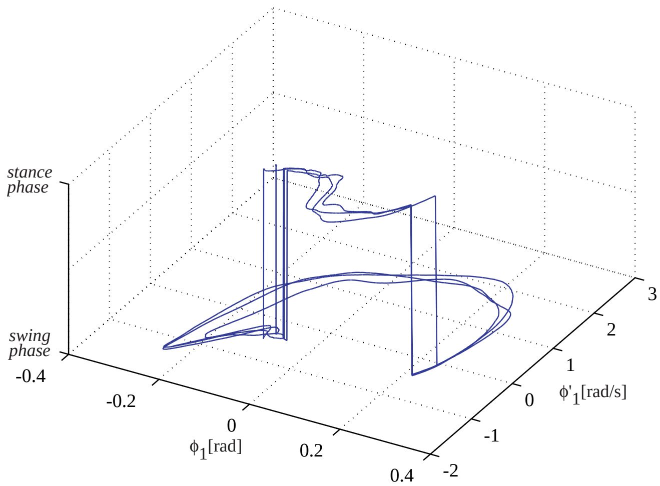

Fig. 15: Phase diagram in $\phi_1, \dot{\phi}_1$ 3D.

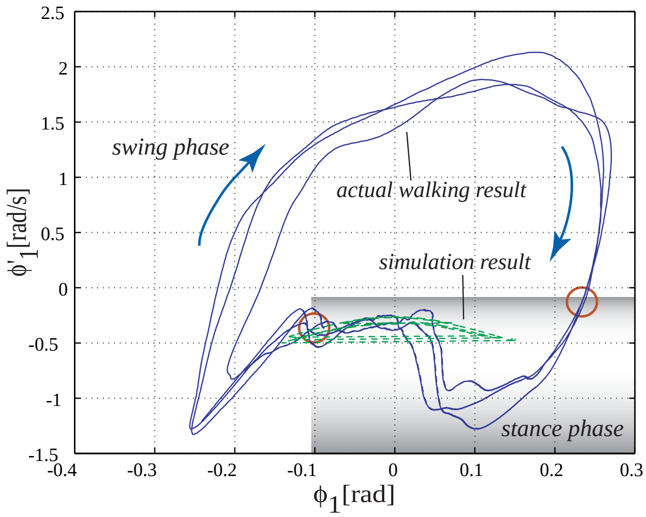

Fig. 16: Phase diagram in $\phi_1, \dot{\phi}_1$ plane.

to achieve active knee supporter for not only lower-limb amputees but also aged persons. We would like to develop the potential of bipedal locomotion control and make it a technology familiar to people.

Fig. 17: Image of power limb.

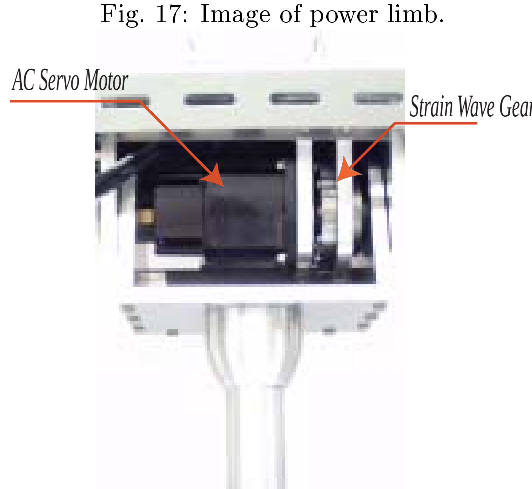

Fig. 18: Drive mechanism of power limb.

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