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Simulation of Human Walking with Powered Orthosis for Designing Practical Assistive Device

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Abstract— **To design a powered assistive orthosis for human walking, we have simulated walking motion with an orthosis. The model dynamics of the coupled human-orthosis is represented by a 10-rigid-link system. In this model there exist rotational joints at lumbar, both thighs and both legs for orthosis, and each joints are controlled by a couple of central pattern generators (CPG) which imitates neuronal system in the spinal cord of mammals. The CPG controller modeled by 18 oscillators which have the sensory feedbacks and generates the joint torques to move the skeletal model of the coupled human-orthosis. This means that we use five actuators for controlling orthosis in the both of sagittal and frontal plane. The parameters of the CPG and the connecting gains are optimized by using a genetic algorithm. We have achieved the successful simulation of stable walking against disturbances with this model. The simulation results indicate the possibility of a practical assistive orthosis with five active joints for stable walking.**

I. Introduction

There exist the needs for the walking rehabilitation of paraplegic patients. The paraplegic patients usually use wheelchairs to move because wheelchairs are only the inexpensive device which can be used for the patients' activity of daily living. Moreover, a wheelchair is usually customized to each patient. Therefore, it is friendly to patients and useful for their activity of daily living. However, wheelchairs bear problems of the inconvenience while overgoing steps and the negative influence on the health because of long seating time. Therefore, it is helpful for paraplegic patients to walk by their legs and watch around from the same eyes height with normal persons.

Many kinds of powered assistive devices for walking have been proposed. Berkeley Robotics & Human Engineering Laboratory developed the exoskeleton orthosis and paraplegic patient walk with the orthosis [1]. In other devices controlled by Central Pattern Generator (CPG), Honda developed powered assistive device for hip joints [2]. CPG is the rhythm pattern generator in the spinal cord of mammals. We developed powered assistive orthosis for the paraplegic patients as shown in Fig. 1 [3]. This system is composed of an exoskeleton orthosis and CPG as the controller. The CPG controller does not require the references of joint angles and can generate a periodic motion associated with the patient's musculoskeletal system. Furthermore, it can adapt to the walking speed or the size and weight of target patients.

Although several kinds of powered orthoses have been proposed, the actuators attached at some joints of the skeletal system can affect mainly on the movements of the body in the sagittal plane. In those orthoses, canes are usually required to stabilize the posture in the frontal plane because they don't equip any actuator acting on the body movements in the frontal plane [1], [2]. If we achieve the posture stability both in the sagittal and the frontal planes with a powered orthosis, the patients can walk without canes, and walk like non-handicapped people.

The final purpose of this paper is to introduce actuators and controllers acting in the frontal and the sagittal plane and achieve the stable walking with powered orthosis in three dimensional spaces on the floor. It is important to reduce the number of actuators for the practical design for orthosis, because the weight of orthosis should be minimized. Therefore, only one actuator has been introduced at the lumbar in the frontal plane. In order to design the orthosis, we take a model-based approach which simulates walking of a coupled human-orthosis model. The orthosis is controlled at each joint by CPG, which has been successfully applied to walking simulation with a three dimensional musculoskeletal model [4]. The robustness of the controlled system has been verified by adding external forces in the frontal plane. The simulation results will give a guideline for a new practical powered orthosis with a small number of actuators.

II. Simulation Model

A. Three dimensional simulation model

Taga suggested that bipedal walking is generated when a rhythm pattern formed by the neuronal system which is CPG cooperated mutually with the pendulum-like rhythm pattern produced by the body's dynamics [5]. Based on this Taga's investigation, Hase and Yamasaki achieved the model that

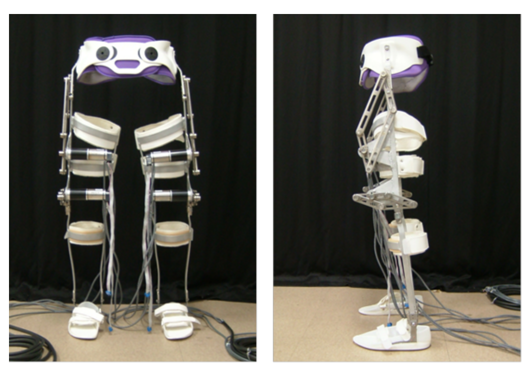

Figure 1. Proposed powered assistive orthosis.

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simulates more precisely human movements in three dimensional spaces [4]. Tagawa added new controller to the model proposed by Hase and Yamasaki, and he proposed more robust controller against the disturbance [6]. They proposed the neuro-musculo-skeletal model for simulating actual human gait. The neuro-musculo-skeletal model can move in three dimensions and consists of rigid links system, the muscles attached to the links, and the neuronal system which is CPG investigated by Taga. The CPG send signals to muscular system as the command for the generated forces.

This neuro-musculo-skeletal model can be developed for simulation of paraplegic patients walking with orthosis. We propose coupled human-orthosis model as shown in Fig. 2. The sticks represent rigid links and cylinders represent pin joints with one Degree of Freedom (DoF). The direction of cylinders represents rotational direction of each joint. For example, knee and hip joints are allowed to rotate in sagittal plane. On the other hand, lumber joint is allowed to rotate in frontal plane. This model is composed of 10-rigid-link, active joins and passive joints. 10-rigid-link means feet, lower thighs, femurs, pelvis, upper body and arms. The geometric and inertial parameters are determined based on [7]. In Fig. 2, the inside of the dotted square represents both of a patient and orthosis, outside represents a patient only. We assume that the skeletal system of a patient and the worn orthosis makes one rigid link system. Therefore the links in the dotted square have total weight of human and orthosis.

Some joints between the links are passive and the other joints are active. All of active joints are controlled by CPG. The active joints in dotted square are controlled by actuators installed on the orthosis, and the others are controlled by the patient's muscles with the corresponding CPG. One pair of CPG unit is placed at each active joint. The CPG pair sends the command to the corresponding muscles or the actuator of orthosis at the joint, and receives the sensory feedback. The CPG unit has been modeled by nonlinear oscillators [8]. One pair of the oscillators is attached to each active joint. The output of one oscillator is corresponding to the flexion torque and the output of the other oscillator is for the extension at the active joint. The dynamics of each oscillator is given by as the following nonlinear differential equations:

$$\frac{1}{T_r}\ddot{x}_i + x_i = -\sum_{j=1}^{n} a_{ij}y_i - bz_i + u_i + Feed_i \qquad (1)$$

$$\frac{1}{T_a}\dot{z}_i + z_i = y_i \qquad (2)$$

$$y_i = max\,(0, x_i) \qquad (3)$$

in these differential equations, x_i is the state variables of the i-th oscillator, z_i is the other state variable representing the fatigue of the oscillator, T_r and T_a are time constants, a_{ij} is the weight of the interconnection between neural oscillators, b is the fatigue constant, u_i is continuous stimulation from higher center in mammals, $Feed_i$ is the sensory feedback signal from the receptor and y_i is the output of the oscillator.

The moment of passive joints are given by the following nonlinear function in a similar way to the literature [8]

$$passive_i(q_i, \dot{q}_i) = k_{i1}\exp[\{k_{i3} + (q_i - \overline{q_i})\}] - k_{i4}\exp[-k_{i5}\{(q_i - \overline{q_i}) + k_{i6}\}] + c_i\dot{q}_i \qquad (4)$$

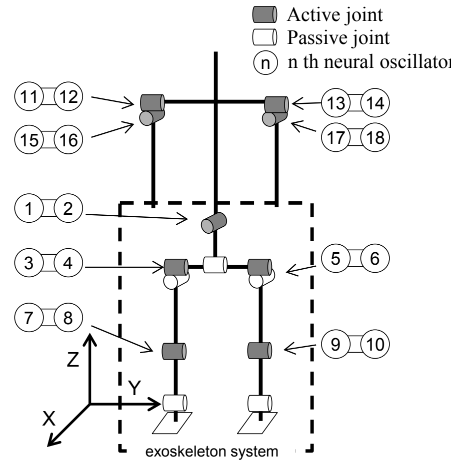


Figure 2. The rigid-link system and the neural oscillators. The cylinders represent pin joints with one degree of freedom of rotation. The circles denote the neural oscillators.

in this equation, $passive_i$ is the passive moment of the i-th joint, and $k_{i1} \sim k_{i6}$ are the coefficients. We determined these coefficients based on the literature [9] and range of motion for walking with orthosis. When one of the joint angles reaches to the limit, the reaction force is generated by the assumed spring and damper.

The most important thing in our model is the number of active joints. We use five active joints for inside of dotted square. In sagittal plane four active joints are allowed to rotate and in frontal plane only one actuator is allowed to rotate. That means only five actuators are used for orthosis.

III. DESIGNING OF WALKING PATTERN

A. The method of tuning parameters

Hase and Yamasaki [10] proposed a numerical search method: genetic algorithms (GA) to determine the parameters by maximizing the criteria for evaluating walking motion. The algorithm for the numerical calculation consists of the following three steps. First, walking motion is generated by numerically solving the differential equations of (1)~(3) with the initial values of parameters of CPG. Second, the generated walking motion is evaluated with the criterion. Third, the parameters of CPG are adjusted to improve the value of the criterion. These steps are repeated until the improvement stops to increase. It is important to set relevant criterion for getting stable gait. Therefore we describe the criterion in the next section.

B. Evaluation criteria

In this study, we need to tune the parameters for designing orthosis and check the robustness of the coupled human-orthosis controlled by CPG with the acquired parameters. To obtain the desired property of the control system of coupled human-orthosis, the appropriate definition for the evaluation criteria is quite important. For defining such appropriate criteria, we consider six points described below.

- Not to stumbling

Almost of all causes of falling down while walking were stumbling in our test simulation with random values of CPG parameters, so that we realized that the evaluation of foot clearance is important. The value of 0.02 in (5) is determined through a lot of simulations.

$$C = 1 - \frac{foot\ clearance}{0.02} \tag{5}$$

- The variance of walking steps

Increasing of the variance causes falling down and reduces the energy efficiency of walking. $\bar{l}$ is the average of step length, and l is the step length.

$$L_{d1} = (\bar{l} - l)^2 \tag{6}$$

- Consumption of energy [11]

τ_i is the torque and $\dot{\theta}_i$ is angular velocity of the i-th joint. M[kg] is body weight. $E_{metabolic}$ is the energy rate of basal metabolism in the body in the literature [12].

$$E = \frac{E_{metabolic} + \int \sum_i |\tau_i \dot{\theta}_i|}{Mgd} \tag{7}$$

$$E_{metabolic} = 0.685M + 29.8 \tag{8}$$

- Smoothness of joint angle trajectories

Abrupt movements in joint trajectories mean big torques at the joints and may cause instability of the control system. τ_i is the torque of i-th joint and τ_r is rated torque of motor.

$$T = \int \sum_i \left|\frac{\tau_i}{\tau_r}\right|^3 \tag{9}$$

- Walking speed

It is well known that there exists the optimal speed for energy efficient walking. v_r is referential speed and v is actual walking speed of the model.

$$V = (v_r - v)^2 \tag{10}$$

- Straight walking

$\overline{\theta_L}$ is the average of lumber joint angle and θ_L is lumber joint angle.

$$L_{d2} = (\overline{\theta_L} - \theta_L)^2 \tag{11}$$

We take the weighted linear combination of the six terms as the evaluation criteria, as in (12). Maximizing numerically the criteria by GA, we obtain the parameters of CPG.

$$J = w_0 - w_1 C - w_2 L_{d1} - w_3 E - w_4 T - w_5 V - w_6 L_{d2} \tag{12}$$

IV. RESULT

A. The result of GA

Fig. 3 shows the simulated walking patterns with the optimized parameters of CPG. At the beginning of the search process, the model could not walk, that is, fell down. After several iterations, the model obtained the ability of continuous walking, but the gait was not stable. After the search converged, the model could walk smoothly and efficiently.

B. Walking without disturbances

The simulation model could walk very likely to normal human walking although DoF and the number of the active joints significantly less than those of actual human. Fig. 4 shows the angles of right hip, right knee and lumbar in a gait cycle. The solid line shows the result of simulation and the dotted line shows the measured angle of normal person's walking in the literature [13]. It is observed that the simulated angles correspond well to the measured one. However, some differences between the simulated results and the measured one of normal walking are observed. For examples, in stance phase the simulated hip angle is smaller, and the simulated knee angle is larger. The simulated lumbar angle is larger. Although our model for the coupled human-orthosis is quite simpler than actual human neuro-musuculo skeletal model, these differences in Fig. 4 mainly come from the fact that we reduce DoF and the number of active joints in the lower body for representing the restricted situation by the orthosis.

C. Robustness against external disturbances

To demonstrate walking stability in the frontal plane, various external forces were added to the model while walking. Fig. 5 shows the stick picture of continuous walking. We provided two models. One has an active lumbar joint which is the same model above and the other one has a passive lumbar

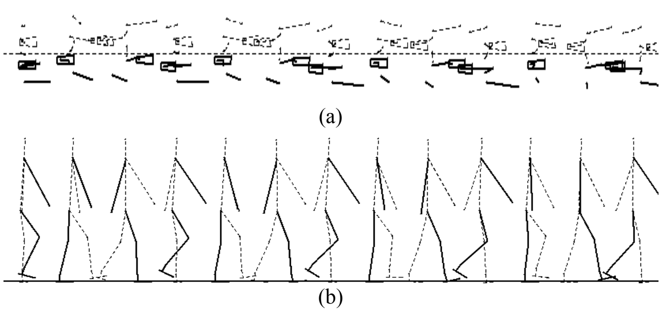


Figure 3. Simulated walking pattern. (a)Top view. (b)Side view.

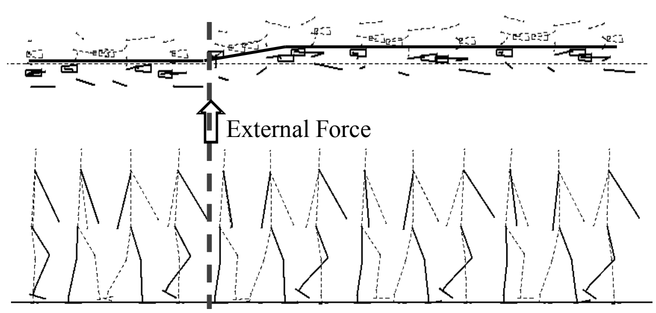
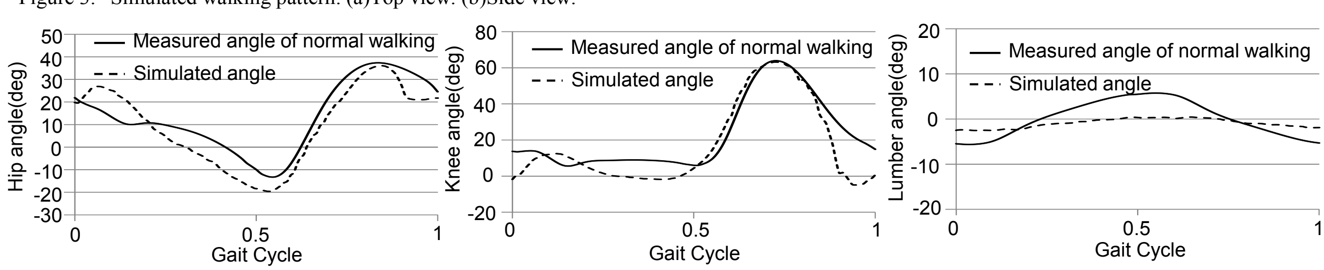


Figure 5. Continuous walking against disturbance force.



(a) (b) (c)

Figure 4. Comparison of simulated angles with measured angles (a)Hip Angle. (b) Knee Angle. (c)Lumber Angle

joint where the output from the CPG is cut. The result is shown in Table 1. By comparison with two models, the model with active joint can continue to walk after disturbance more than another model which has passive lumbar joint. Furthermore lumbar joint torque is shown in Fig. 6, and the y-axes-position of right foot, left foot and Center of Gravity (CoG) are shown in Fig. 7. In the model with active lumbar joint, the position of CoG can be controlled at between right and left foot and falling down is prevented. The lumbar joint generates large torque when external force is added to the model and the upper body is adjusted against the disturbance on the frontal plane. On the other hand the model which has passive lumbar joint cannot control upper body, therefore the y-axes-position of CoG becomes to be located at the side of foot-position and the model fall down. These results have proved that the active control on lumbar joint by CPG contributes the potential of balancing the upper body in frontal plane with the other active joints at shoulders. However, the case of (*) in Table 1 is a specific pattern. Even if smaller external forces added to the model at the same time and direction, the model fall down. We consider this is affected by the passive joint of hip in frontal plane. If a large external force add to the model, the hip joint in frontal plane rotate large, and foot-position become to be located at the side of y-axes-position of CoG. Therefore, the case of (*) is seemed to be happened.

V. Conclusion

In order to design safer orthosis against disturbances, we proposed the coupled human-orthosis model that is composed of rigid links, CPG and passive joints. Although the number of active joints for the orthosis is only five, the model walks similar to no-handicapped people. Moreover, the model adopts to external forces in frontal plane otherwise the active joint in frontal plane for the orthosis is only one. The results suggest a useful guideline for designing a new powered orthosis.

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TABLE I. Responses to External Forces

External Force Direction			Y			-Y		
External Force (N)			50	70	100	50	70	100
Passive Lumbar Joint	Gait Cycle (%)	0	×	×	×	×	×	×
		50	×*	○	○	×	×	×
		100	×	×	×	○	×	×
Active Lumbar Joint	Gait Cycle (%)	0	×*	○	×	○	×	×
		50	○	○	○	○	○	○
		100	○	○	×	×*	○	×

○:Continue walking. ×: Fall down

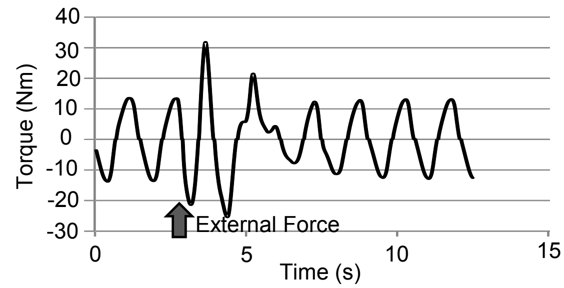
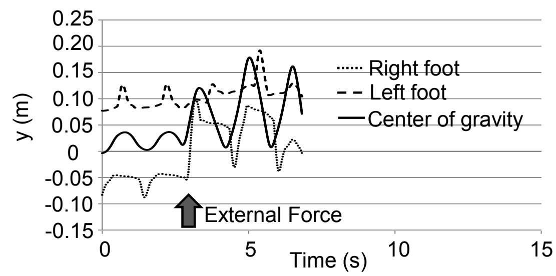
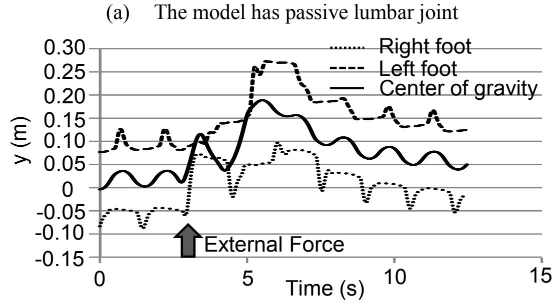


Figure 6. The torque of lumbar joint.



(a) The model has passive lumbar joint



(b) The model has active joint

Figure 7. y-axes-position of foot and center of gravity.

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