Leg Control based on Human Motion Prediction Using Motion Sensor for Power Assist Suit without Binding Knee

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Takuya Inoue, Shinnosuke Nomura, Yasutake Takahashi, Masayuki Kawai, and Yoshiaki Taniai
Graduate School of Engineering, University of Fukui
Bunkyo 3-9-1, Fukui, Fukui, 910-8507, Japan
E-mail: {tinoue, snomura, yasutake}@ir.his.u-fukui.ac.jp, m_kawai@u-fukui.ac.jp, taniai@rbt.his.u-fukui.ac.jp

Abstract—Recently, power assist suits which support human physical activities have been researched. We are developing a power assist suit for workers in a nuclear power plant. If a disaster happens, the workers have to wear heavy radiation protective equipment. The power assist suit is supposed to support the wearer so that it reduces the load of the radiation protection equipment during an operation.

This paper proposes a power assist control method based on motion prediction using 9-axis motion sensors. The power assist suit enables rapid power assist because the motion sensor can detect the start of walking motion in real time. A motion database consists of angles and angular velocities of wearer's chest, lower limbs, and joint angles of the power assist suit. The power assist suit recognizes the motion of the wearer based on the database. Then, it assists the wearer based on the estimation of the motion of the wearer. We conduct experiments to evaluate the proposed method.

I. Introduction

Recently, in the nursing care field, a labor shortage is serious because people in need of nursing care are increasing and the burden of nursing care is relatively heavy. The agriculture field also has similar problems that aging of farmers reduces the activity of the farming. Power assist suits are supposed to solve these problems[1], [2]. It supports caregivers in the nursing care field, the rehabilitation of senior people with the decline of the standing and reduction of turnover rate of senior people.

Currently, power assist suits are used in various fields not only agriculture, medical and welfare services. Our research target is a support system for workers in nuclear power plants. There are typical three approaches to control a power assist suit so far. The first approach is based on myoelectric signals using an electromyograph(EMG)[2], [3], [4]. It detects the human intention by measuring the action potential of muscle, and the power assist suit assists the human action according to the human intention. Since action potential occurs before about 50 [ms] than the muscle to contract, power assist suits enable rapid assist. However, it suffers from human sweat[5]. This method is not suitable for this research so that a worker easily sweats in a radiation protective equipment because the equipment is made of highly airtight materials and temperature and humidity are high in it. The second approach uses the sensors that can measure the hardness of muscle. Unfortunately, it suffers from the sweat and fatigue of the

muscle. The third approach uses a force sensor[6], [7]. Force sensor attached to the foot bottom of the power assist suits detects the human centroid position. The power assist suit estimates the human intention based on the human centroid position and assists the human walk. This method needs one or two step of the walk to recognize the walk so that it is hard to realize rapid assist control.

We propose a novel approach for power assist control based on human motion estimation using the 9-axis motion sensors. The motion sensor is able to measure the motion of the wearer in a high temperature and humid environment. Our power assist suit does not bind knee unlike popular power assist suites and a wearer can move his/her legs freely at beginning of the motion so that it can detect the start of walking motion quickly. Motion estimation and assist are realized based on a database that consists of angles and angular velocities of subjects wearing the power assist suits and its joint angles at waists and knees. This paper conducts experiments to evaluate the proposed method.

II. Power Assist Suit without Binding Knee

1) *Power assist suit*: Figures 1 and 2 show power assist suit (Activelink Co., Ltg., Japan) used in this research. It has four geared motors and rotary encoders at the knees and hips joints and their angles are controlled by a PID controller. There is no motor at angle joints. The degree of freedom of the joints is shown in Fig.1(a).

The power assist suit binds a wearer only at shoulders and feet. There are no bindings at limbs of upper and lower legs like other conventional power assist suits usually have. The wearer can move his/her knees freely at the beginning of the motion. This point of our power assist suit is different from the rest.

This power assist suit is developed for a worker transporting the heavy baggage in the nuclear power plant. If a disaster happens, the worker must wear about fifty kg of radiation protective equipment. The worker is also supposed to carry a heavy robot, such as PackBot[8], that searches in the power plant.

Conventional power assist suits are controlled based on some approaches. Force sensor based power assist control is one of them and we also applied the approach to our power

assist suit. Force sensors are attached at bottoms of foots. It estimates the state of legs based on measuring loads of both feet and assists appropriately according to the state of legs. In addition, the other force sensor at back measures the weight of the load hanging on the back. The power assist suit assists the worker to carry the load according to the measured weight of the load. However, we found that this approach cannot distinguish similar motions such as "swinging from side to side" and "walk".

2) *measuring devices*: Figure 2 shows a wearer attaching 5 nine-axis motion sensors and their position and coordinates. The x-axes are vertically upward, y-axes are horizontal, and z-axes are forward. The wearer equips them to the chest and upper and lower legs. The power assist suit distinguishes motions "singing from side to side" and "walk" based on the outputs of the motion sensors correctly. The algorithm proposed by Sebastian O.H. Madgwick[9] is adopted to calculate posture of a motion sensor in this paper. This method uses acceleration, angular velocity, geomagnetism measured by the motion sensor to calculate the posture.

Axes of force sensors are depicted in Fig.1(a). These sensors measure load and moment in three directions. Only the force sensor at the back of the wearer is used to evaluate our proposed method in this paper. The force sensor measures the load on the shoulder of the wearer.

The wearer equips EMG sensors at upper and lower legs to measure the EMG e_t at the rectus femoris and tibialis anterior muscles. They detect the amount of shrinkage of muscle to estimate the muscle strength of legs. In this paper, we use the EMG value e_t applied the ARV process. This process is shows as below.

$$ARV[e_t] = \frac{1}{2T} \int_{-T}^{T} |e_{t+\tau}| d\tau \tag{1}$$

where T is an integration range. This is used to compare the assist performance of the proposed method and the conventional one.
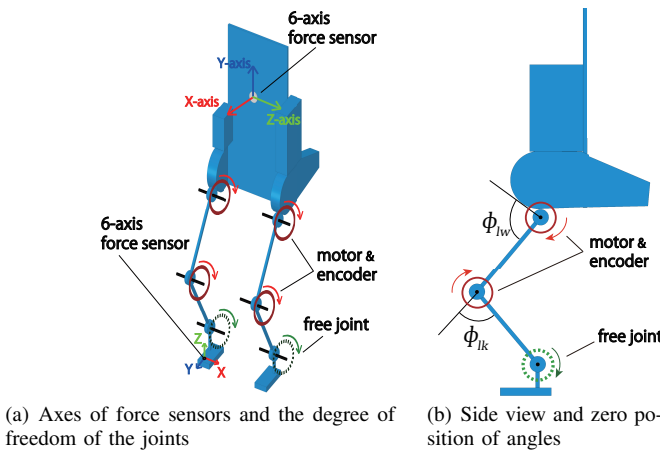

(a) Axes of force sensors and the degree of freedom of the joints

(b) Side view and zero position of angles

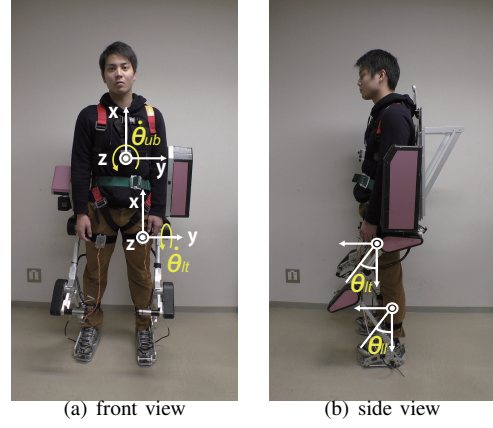Fig. 1. Configuration of Power Assist Suit

(a) front view   (b) side view
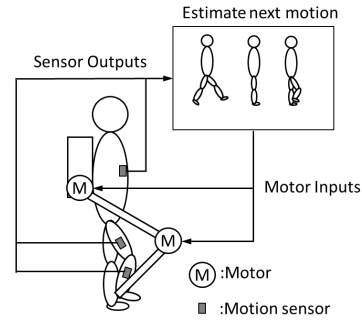
Fig. 2. Axes of Motion Sensors Attached to the Body

Fig. 3. Overview of Proposed Control System

III. LEG CONTROL BASED ON HUMAN MOTION PREDICTION USING MOTION SENSOR

Figure 3 shows the overview of proposed controller using motion sensors for our assist system. Power assist suit recognizes the wearer motion to assist him/her. It estimates appropriate few hundred milliseconds later joint angles of the power assist suit according to the recognized motion to assist the wearer in real-time. The motion estimation is based on a motion database complied in advance. The motion database is composed of data of wearer motion and corresponding leg motion of the power assist suit. It estimates the few hundred milliseconds later joint angles of legs of the power assist suit using the current sequence of angles and angular velocities of motion sensors attached to the wearer based on the motion database. The joint angles of legs are controlled to be the estimated angles by PID controller.

The database includes the sequence data of motion sensor attached to the wearer and joint angles of legs of the power assist suit while the wearer shows motions "staying in an upright position" and "walking." The data of motion sensor is angles $\boldsymbol{\theta}_t = (\theta_{rt}, \theta_{rl}, \theta_{lt}, \theta_{ll})$ and angular velocities $\dot{\boldsymbol{\theta}}_t = (\dot{\theta}_{rt}, \dot{\theta}_{rl}, \dot{\theta}_{lt}, \dot{\theta}_{ll}, \dot{\theta}_{ub})$ of motion sensors attached to the wearer. Indexes rt, rl, lt, ll, and ub indicate right upper leg, right lower leg, left upper leg, left lower leg, and torso,

respectively. The joint angle of power assist suit is defined $\phi_t = (\phi_{rw}, \phi_{rk}, \phi_{lw}, \phi_{lk})$. Indexes rw, rk, lw, and lk indicate right hip, right knee, left hip, left knee of the power assist suit, respectively.

Then motion data of the wearer is defined $\boldsymbol{x}_t = (\dot{\boldsymbol{\theta}}_t, \boldsymbol{\theta}_t)$ at time t. $\boldsymbol{x}_t(0 < t < n)$ is segmented with the window which size is m into sequence data $(\boldsymbol{x}_t, \boldsymbol{x}_{t+1}, \cdots, \boldsymbol{x}_{t+m})$. Figure 4 shows the procedure. The sequence data have two motion category index "standing" c_s and "walking" c_w. One database is for composed of the sequence motion data of m window size and the category index $^c\boldsymbol{w} = (\boldsymbol{x}_t, \boldsymbol{x}_{t+1}, \cdots, \boldsymbol{x}_{t+m}, c_i)$. This database is used for estimation of wearer's motion.

The sequence motion data are divided into two data sets by the motion categories c_s and c_w and assigned to the joint angles of the power assist suit at advanced time $t + \Delta t$. $^s\boldsymbol{w}$ is composed of the motion sequence data categorized into "standing" and the joint angles of the power assist suit at advanced time $^s\boldsymbol{w} = (^s\boldsymbol{x}_t, ^s\boldsymbol{x}_{t+1}, \cdots, ^s\boldsymbol{x}_{t+m}, ^s\boldsymbol{\phi}_{t+\Delta t})$. $^w\boldsymbol{w}$ is composed of the motion sequence data categorized into "walk" and the joint angles of the power assist suit at advanced time $^w\boldsymbol{w} = (^w\boldsymbol{x}_t, ^w\boldsymbol{x}_{t+1}, \cdots, ^w\boldsymbol{x}_{t+m}, ^w\boldsymbol{\phi}_{t+\Delta t})$. The databases $^s\boldsymbol{w}$ and $^w\boldsymbol{w}$ are used for estimation of appropriate joint angles of the power assist suit at advanced time $t + \Delta t$.

Power assist suit recognizes wearer's motion based on k-nearest neighbor method using the database $^c\boldsymbol{w}$. Motion data of wearer at current time t is defined $\boldsymbol{x}_t = (\dot{\boldsymbol{\theta}}_t, \boldsymbol{\theta}_t)$. The sequence data with window size m is defined $^q\boldsymbol{w}_t = (\boldsymbol{x}_{t-m}, \boldsymbol{x}_{t-m+1}, \cdots, \boldsymbol{x}_t)$. It calculates normalized euclidean distance d_t between one of the data $^c\boldsymbol{w}$ and $^q\boldsymbol{w}_t$. It chooses k data with the smallest distances based on k-nearest neighbor method and extracts a set of category IDs $\boldsymbol{c} = (c_1, c_2, \cdots, c_k)$ each of which is one of the two motion categories. Then the k-nearest neighbor algorithm outputs one of the categories, that is, c_s for category "standing" if the number of "standing" categories in $\boldsymbol{c}$ is greater than the one of "walking" categories, or else category c_w for "walking".

The normalized distance is calculated as below.

$$\boldsymbol{\mu} = \frac{1}{n} \sum_{k=1}^{n} \boldsymbol{x}_k \qquad (2)$$

$$\boldsymbol{\sigma} = \frac{1}{n} \sum_{k=1}^{n} (\boldsymbol{x}_k - \boldsymbol{\mu})^{\mathrm{T}} (\boldsymbol{x}_k - \boldsymbol{\mu}) \qquad (3)$$

$$d_t^2 = (^q\boldsymbol{w}_t - ^c\boldsymbol{w}_t) \Sigma_t^{-1} (^q\boldsymbol{w}_t - ^c\boldsymbol{w}_t)^{\mathrm{T}} \qquad (4)$$

where $\sum_t^{-1}$ is variance matrix which has variance vector $\boldsymbol{\sigma}$ on the diagonal and T shows transposition of the vector. $^c\boldsymbol{w}_t$ is an arbitrary sequence data in database $^c\boldsymbol{w}$.

Then it estimates the appropriate joint angles of the power assist suite at time $t + \Delta t$, $\phi_{t+\Delta t}^d$, according to the estimated motion of the wearer based on k-nearest neighbor algorithm. If the estimated motion is "standing", it chooses the database $^s\boldsymbol{w}$ or else $^w\boldsymbol{w}$. $\phi_{t+\Delta t}^d$ is calculated based on k-nearest neighbor algorithm with the database and the current motion data $^q\boldsymbol{w}_c$. Overview of estimating appropriate joint angles of the power

assist suit is shown in Figure 5 and the algorithm of these processes is shown in Algorithm1.

It calculates the input of the joint motor u_t using Eq. (5).

$$u_t = -k_p(\phi_{t+\Delta t}^d - \phi_t) - k_i \sum_{n=0}^{t} (\phi_{n+\Delta t}^d - \phi_n)$$
$$-k_d \left((\phi_{t+\Delta t}^d - \phi_t) - (\phi_{t+\Delta t-1}^d - \phi_{t-1}) \right) \qquad (5)$$

where ϕ_t^d is the desired joint angle and ϕ_t is the current joint angle of power assist suit at time t. k_p, k_i and k_d are proportional, integral and differential gains, respectively.
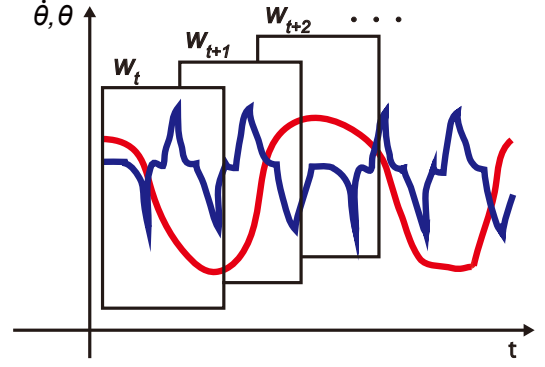

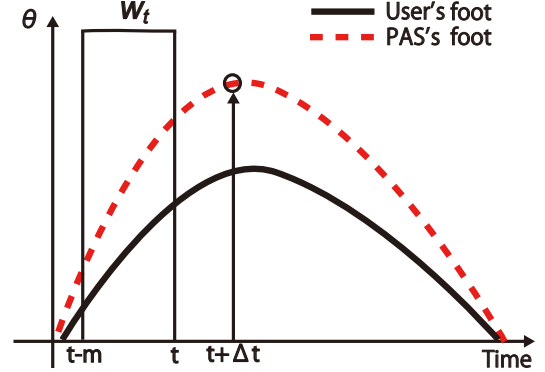Fig. 4. Data segmentation with a window for building motion database

Fig. 5. Estimation of future joint angle

IV. EXPERIMENTS

Experiments are conducted to evaluate the validity of the proposed method. One wearer who is the early 20s of a male student participates in the experiments. The experiments are set up as follows: Sequence data of joint angles of the power assist suit and the motion data of the wearer while he demonstrates standing and walking motions are collected. Figure 6 shows an example of the data collection. The sequence data are assigned to one of the two categories "standing" and "walking" motions by hand and the classification database $^c\boldsymbol{w}$ is built. The sequence of each motion data is compiled to one
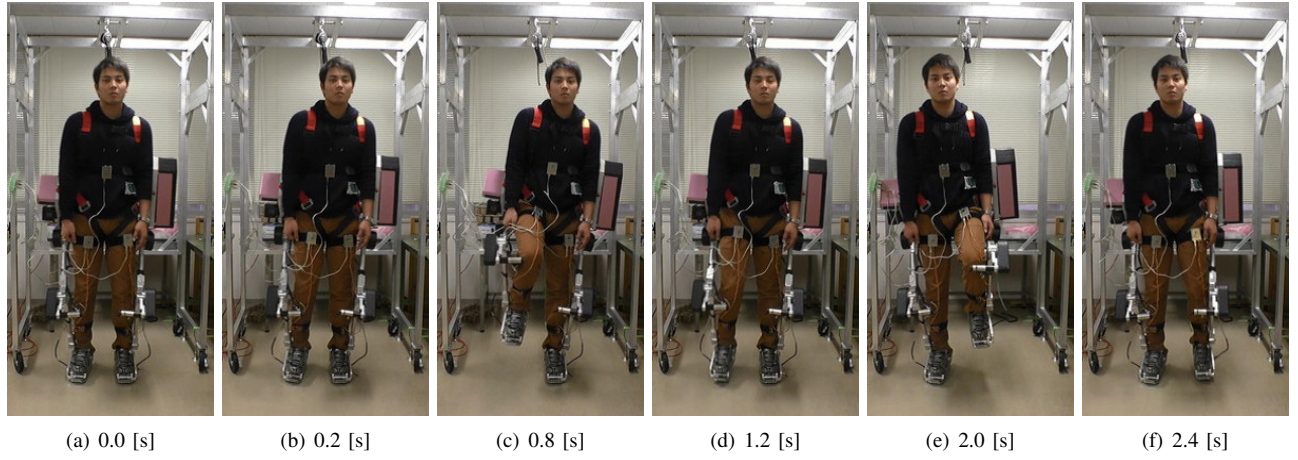
(a) 0.0 [s]   (b) 0.2 [s]   (c) 0.8 [s]   (d) 1.2 [s]   (e) 2.0 [s]   (f) 2.4 [s]

Fig. 6.   Motion of Wearer wearing Power Assist Suit without Assist Control

(a) 0.0 [s]   (b) 0.2 [s]   (c) 0.8 [s]   (d) 1.2 [s]   (e) 1.8 [s]   (f) 2.2 [s]
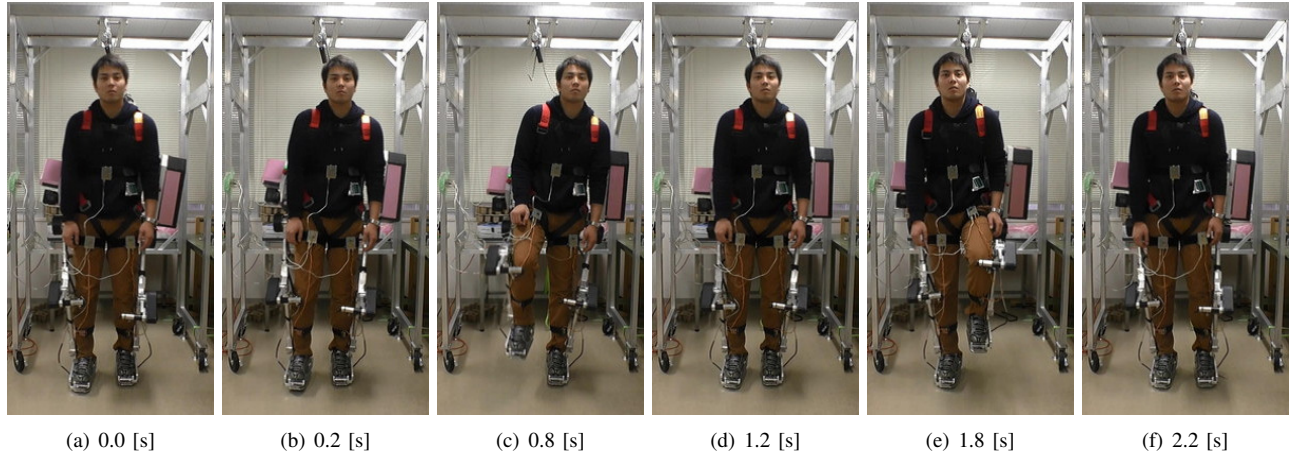
Fig. 7.   Motion of Wearer wearing Power Assist Suit with Assist Control based on Wear's Motion Estimation

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Algorithm 1 Calculation of appropriate joint angle of power assist suit

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Set up databases $^c\boldsymbol{w}$, $^s\boldsymbol{w}$ and $^w\boldsymbol{w}$ from $\boldsymbol{x}_t$
at current time t
$\boldsymbol{c} = knn(\boldsymbol{w}_t,^q\boldsymbol{w}_t)$: $c = c_s$ or c_w
if $c = c_s$ **then**
   recognizes the current motion as "standing" motion
   $\boldsymbol{\phi} = knn(^s\boldsymbol{w}_t,^q\boldsymbol{w}_t) : \boldsymbol{\phi} = (\phi_1, \phi_2, \cdots, \phi_k)$
   $\phi_{t+\Delta t}^d = \frac{1}{k}\sum_{i=0}^k \phi_i$
else
   recognizes the stepping motion
   $\boldsymbol{\phi} = knn(^w\boldsymbol{w}_t,^q\boldsymbol{w}_t) : \boldsymbol{\phi} = (\phi_1, \phi_2, \cdots, \phi_k)$
   $\phi_{t+\Delta t}^d = \frac{1}{k}\sum_{i=0}^k \phi_i$
end if
return $\phi_{t+\Delta t}^d$

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of two databases for "standing" and "walking" motions $^s\boldsymbol{w}$ and $^w\boldsymbol{w}$. Then the proposed method is applied to the power assist suit based on the databases while the wearer stands and

walks in turn. Figure 7 shows the motion of the wearer and the power assist suit with the power assist control based on the proposed method.

Figure 9 shows the sequence of actual and estimated angles of left knee and hip joints while the power assist suit assists the wearer based on the proposed method. The wearer starts from standing, demonstrates walking motion three times in the right and left legs, and stands again. Estimation parameter Δt is set to 500 ms. The PID gains, k_p, k_i and k_d are set by trial and error so backdrivability becomes lower. The injure risk of wear is still low even if power assist suit failed to estimate the human motion because it still keep enough backdrivability. From 0 to about 3 seconds, the wearer keeps standing, demonstrates walking motion from around 3 to 9 seconds, and then returns to standing motion again. Figures 9(b) and 9(d) show the data sequence of the actual and estimated angles of knee and hip joints between 3 to 5 seconds, respectively It shows that the power assist suit estimates the angle in 500 [ms] future reasonably. The joint angle of the knee does not follow the desired angle during
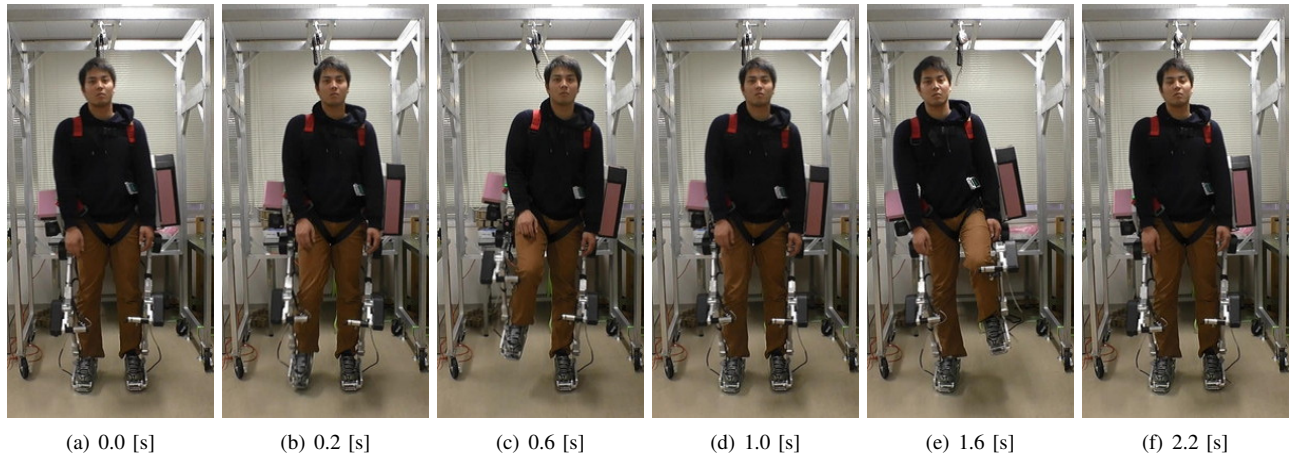
| (a) 0.0 [s] | (b) 0.2 [s] | (c) 0.6 [s] | (d) 1.0 [s] | (e) 1.6 [s] | (f) 2.2 [s] |

Fig. 8. Motion of Wearer wearing Power Assist Suit with Assist Control based on Force Sensors

"standing" motion because the PID gains and motor output is too small. The PID gains are set to relatively small values because the power assist suit compensates backdrivability so that the wearer can move his legs by himself against the controller's output if necessary.

We compare the proposed method using the motion sensors and the conventional method using force sensors to show the effectiveness of the proposed method. The wearer shows standings, starts walking motion three times in the left and right, then comes back to standing, again. Figure 8 shows the motion of the wearer and the power assist suit with the power assist control based on the foot force sensors. The wearer's walking motion shows that he has to move his center of the body in left and right sides more widely than our proposed method (Figure 7). The reason is that he has to shift from one foot to the other so that the foot force becomes much bigger than the other and the controller recognizes the leg as supporting correctly.

Fig.10 We evaluate the assist performance according to the force sensor at back of the wearer. Figure 10 shows that the proposed method successfully reduces the force of the back so that the load to the wearer becomes much lighter. It measures about 300 [N] when the wearer is assisted based on foot force sensors or not assisted at all, it measures about 0 [N] at the standing and about 100 [N] at the walking motion in case of our proposed method. The results show the effectiveness of the proposed method clearly.

We also investigate activities of muscles based on EMG at upper legs during the assist controls. Figures 11, 13 and 12 show sequences of EMG values of the wearer and joint angle of the power assist suit in cases of no assist control, with assist control based on the proposed method and the conventional method based on foot force sensors. The wearer keeps standing from 0 to about 2 seconds, starts walking motion from 2 to about 7 seconds, and come back to standing again. The figures show that EMG values increase during the move the legs in all cases. The EMG values at anterior tibialis muscle are higher than that of rectus femoris. The reason seems to be that the

ankles are not supported as the ankle joints are not supported by the motors. Tibialis muscle is responsible for the walk to support the ankles. The power assist suit cannot decrease the load on the ankles. Figure 12 that the EMG values do not decrease even with the power assist. It shows that the wearer has to activate muscles during the lifting and putting down the legs even if the wearer is supported by the power assist suit reasonably.

V. Conclusion

This paper proposed power assist control system based on the estimated wearer's motion using the motion sensors for a power assist suit without knee binding. It recognizes the current wearer motion and estimates future joint angle of power assist suit based on motion databases, then it assists the wearer in real-time. Experimental results showed the validity of the proposed assist system. As one of future work, it should assist various motions not only standing and walking motion, e.g., forward-backward and side walking, squat motion and swing the body.

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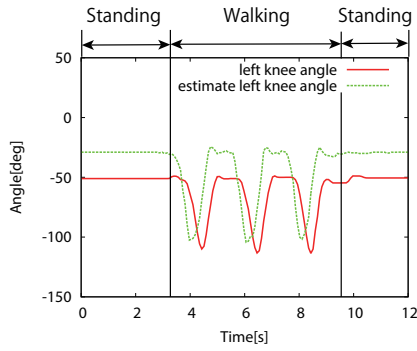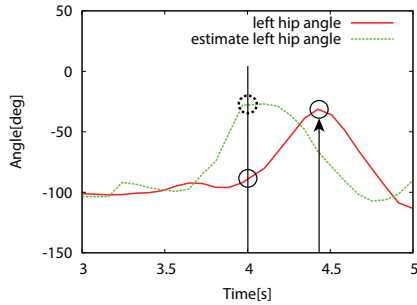
(a) Knee Joint while standing, walking, and standing
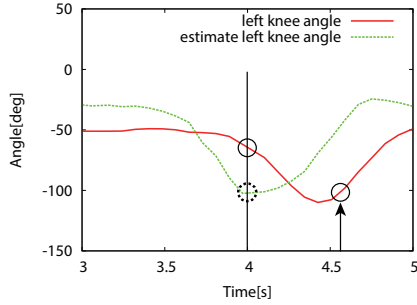
(b) Knee Joint between 3 to 5 seconds
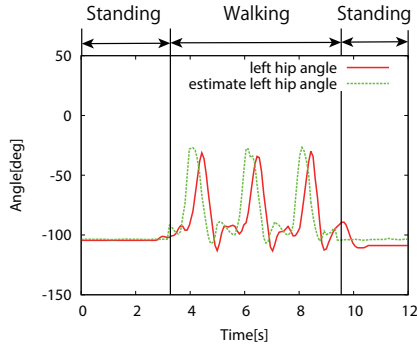
(c) Hip Joint while standing, walking, and standing

(d) Hip Joint between 3 to 5 seconds

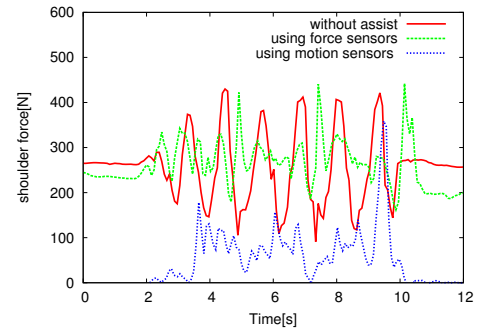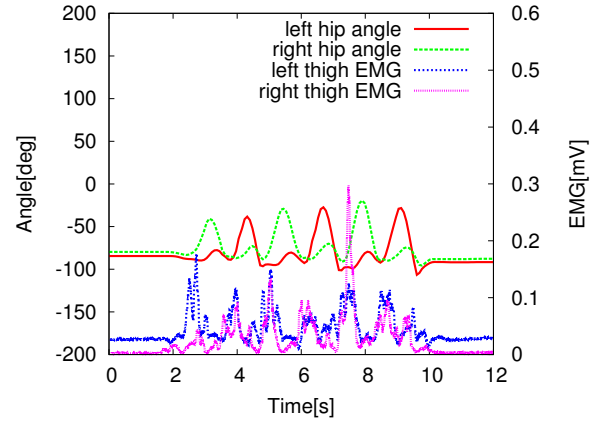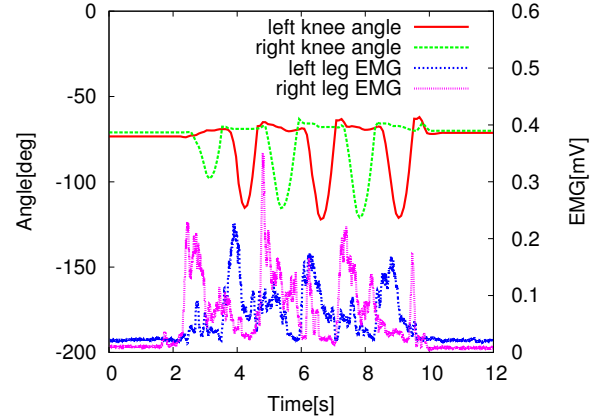Fig. 9. Actual and Estimated Angles at Knee and Hip Joints during Power Assist

Fig. 10. Load at back of the wearer during motions

(a) Hip Joint Angle and EMG of the Left Rectus Femoris
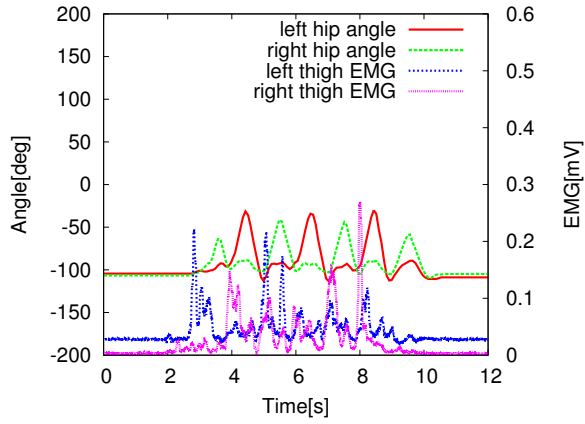

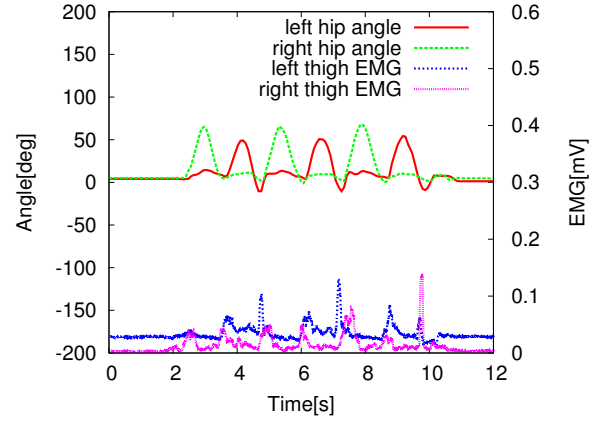(b) Knee Joint Angle and EMG of the Left Anterior Tibialis Muscle

Fig. 11. Sequence of Joint angles and EMG during the motion without power assist

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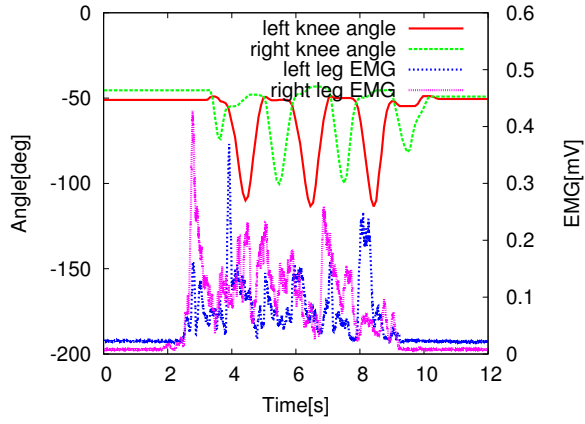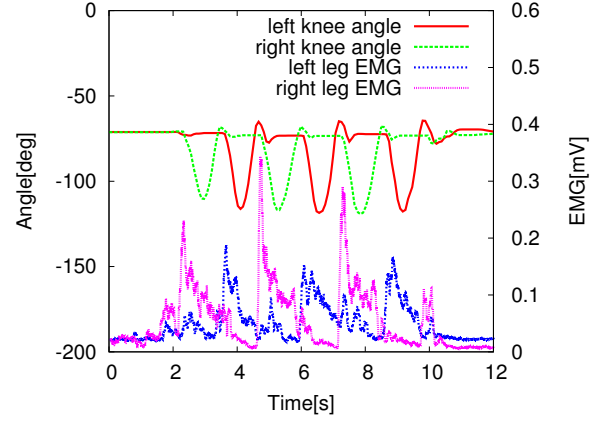[9] S. O. Madgwick, *An effcient orientation filter for inertial and inertial/magnetic sensor arrays*, 2010.

(a) Left Joint Hip Angle and EMG of the Left Rectus Femoris

(b) Left Joint Knee Angle and EMG of the Left Anterior Tibialis Muscle

Fig. 12. Sequence of Joint angles and EMG in proposed method using the motion sensors

(a) Hip Joint Angle and EMG of the Left Rectus Femoris

(b) Knee Joint angle and EMG of the left anterior tibialis muscle

Fig. 13. Sequence of Joint angles and EMG during the motion with a conventional power assist method based on foot force sensors.