Abstract—In this paper we propose a framework for synchronization based control (SBC) using neural oscillators for motion assist. A neural oscillator is used to accomplish synchronization and entrainment between periodic motions by the human and robot. The mutual joint torque between the human and robot is used as an external input signal for the neural oscillator, which generates the desired trajectory of a robot joint angle, so that the robot motion synchronizes with the external mutual joint torque. The validity and feasibility of the proposed method is examined from three points of view. The first is whether synchronization of action between human and robot can be realized. The second is whether the assist effect can be obtained, and the third is whether the proposed method has an acceptable level of usability for the user. We explored those three points of view by conducting computer simulations on a human-motion assist system and experiments with a joint torque sensing robot suit.

I. INTRODUCTION

As time progresses and society advances, headway is being made in robotics research, resulting in benefits not only in the field of industry, but also in the fields of welfare and medicine. Many attempts have been made to develop extremity exoskeleton robots or a power assist suit capable of assisting people to walk or augmenting human strength. Take BLEEX and HAL as examples. The BLEEX project has developed an energetically autonomous exoskeleton capable of carrying its own weight plus an external payload. Using the information from the sensors in the sole of the foot, the controller determines which phase BLEEX operates at, and which of the three dynamic models should be applied to control the exoskeleton [1][2]. It was developed for walking support and rehabilitation for physically weak people. The system is controlled by a Phase Sequence control method using EMG signal and floor reaction forces as control input signals [3]. Generally speaking, those control methods are ways of outputting joint torque presumed by kinematics and then supplementing the operators’ insufficient force [4]. We conclude that there are two main approaches to control the exoskeleton: one is that human user’s motion or torque is measured or presumed by the robotic suit, which provides sufficient force for the user to move, as shown in Fig. 1. The other way is that the robotic suit’s motion or torque is designed beforehand and the human user is required to move along the provided trajectory, as shown in Fig. 2.

Consequently somewhat inflexible and maladaptive patterns of locomotion have been produced by those control methods, and users who lack the power of locomotion may feel unnatural operating such a system. As the motion assist suit has to be worn by the human user, the problem of how to improve affinity with machine/human interaction is a major issue for concern.

On the other hand, when people interact with each other, such as nursing a patient, walking side by side or shaking hands, they are able to adapt to make one synchronized motion. When a nurse assists a patient to walk, the nurse predicts the patient’s future motion and simultaneously adjusts herself in a timely manner to any change of motion. Generally speaking, nurses are expected to follow their patients’ will and provide assistance at appropriate moment, neither too much nor too little. Therefore, the natural physical feature of a motion assist suit stemmed from an intelligent control system that can be thought of as a good avenue to realize natural-like walking. Recently, neural oscillators are applied to control walk [5] and rhythmic motion [6] by robots in order to generate periodic motions synchronized with the environment. In addition, our primary study on human-robot handshaking was based on neural oscillators, and our simulation and experiments verified the validity and effectiveness of this approach [7]. For assisted walking, we believe that the synchronization and the entrainment between the motions of the patient and nurse are the basic phenomena, which can be prospectively generated by the neural oscillator, which makes use of its distinctive feature. Mutual force between the human user and the assist suit is the input signal of the neural oscillators. The output signals are used for the desired trajectories of the assist suit’s joints. Along with the external force applied on the assist suit being fed back into the neural oscillators repeatedly, the motion of the assist suit is the timely synchronization with human motion and entrained to the same period. We believe that this method, based on assist suit-human interaction can guide both of them to create a smooth synchronized motion. We drew this framework in Fig. 3. In addition, it is necessary that the motion assist suit has the ability to adjust its patterns of motion according to the patient’s intention and physical
ability. In other words, if this patient has little power of locomotion but wants to walk in his own pace actively, or just likes to request the assist suit to take him for a walk passively, such active and passive styles of motion assist can also be realized by adjusting the strength of the synchronization. That is to say, the motion assist suit is expected to have an acceptable level of usability for the user.

Furthermore, neural oscillators can also be applied on motions with no-fixed frequency by adjusting its time constants \( T_r \) and \( T_a \) dynamically. So neural oscillators can be widely used in periodic motions.

![Fig. 3 Framework of SBC](image)

In this paper we propose a framework of synchronization based control (SBC) using neural oscillators for motion assist. The validity and feasibility of the proposed method is examined from three points of view. The first is whether synchronization of action between human and robot can be realized. The second is whether the assist effect can be obtained, and the third is whether the proposed method has an acceptable level of usability for the user. We explore these three points of view by conducting computer simulations on a human-motion assist system and experiments with a joint torque sensing robot suit.

In the next section a model of neural oscillators is introduced and the structure of neural oscillator for a motion assist suit is proposed. The simulations on a human-motion assist system are conducted in section III, experiments are conducted in section IV. Finally, the conclusion of this study and future work are explained in section V.

II. NEURAL OSCILLATOR

A. Neural Oscillator

The structure of a neural oscillator unit is shown in Figure 4. The mathematical model of a neural oscillator is called the “Matsuoka model” [8][9] and is based on the following equation as

\[
T_r \frac{dx_i}{dt} + x_i = \sum_{j \neq i} a_{ij} g(x_j) + S_i - b_i x'_i + \text{Input} \tag{1}
\]

\[
T_a \frac{dx'_i}{dt} + x'_i = g(x_i) \tag{2}
\]

\[
g(x_i) = \max(0, x_i) \tag{3}
\]

Where, \( x_i \) is the inner state of the \( i \) th neuron, \( x'_i \) is a variable which represents self-inhibition effect of the \( i \) th neuron, \( T_r \) and \( T_a \) are time constants of the inner state and the adaptation effect of the \( i \) th neuron, respectively, \( b_i \) is a constant which represents the degree of the self-inhibition influence on the inner state, \( a_{ij} \) is a connecting weight from the \( j \) th neuron to the \( i \) th neuron; \( x_j \) is a steady state input of the \( i \) th neuron, the Input is an external signal.

B. Structure of Neural Oscillator for Motion Assist

One neural oscillator consists of two units as shown in Fig. 5, and the output signal is computed as \( \max(0, x_i) - \max(0, x_o) \). Figure 6 shows the input and output signal of one neural oscillator, which can be considered as a controller for one joint. The desired trajectories of joint angles are determined by the output signals of the neural oscillator. The external mutual torque is fed back into the neural oscillator.

![Fig. 6 Model of neural oscillator](image)

\[
T_r \frac{dx_i}{dt} + x_i = -\sum_{j \neq i} a_{ij} g(x_j) + S_i - b_i x'_i + (-1)^{i-1} \text{Input1} + \text{Input2} \tag{4}
\]

\[
T_a \frac{dx'_i}{dt} + x'_i = g(x_i) \tag{5}
\]

\[
g(x_i) = \max(0, x_i) \tag{6}
\]

In order to synchronize the output signal of the neural oscillator to the external force applied, the signal of Input1 is utilized. Torque means mutual joint torque caused by the interaction force between the human user and the assist suit. Input1 is obtained by multiplying torque by gain \( C \). We can change the strength of synchronization by adjusting the values of the gain. For example, if a patient likes to walk at his own pace actively, that will be realized by selecting a large gain. The opposite can also be true by selecting a small gain, whereby passive walking assist can be achieved. Input2 regulates the amplitudes of oscillations. The absolute value of torque is multiplied by gain \( L \) to determine Input2. With the premises of getting stable oscillation, we determine typical values of parameters for neural oscillator as follows, \( a_{ij}=1.2 \), \( b_i=2.5 \), \( S_i=2.0 \). \( T_r \), \( T_a \) and gain \( C \) are going to be determined as simulation and experiment requirement, so those values will be discussed in the next section.

III. SIMULATION ON ASSIST SYSTEM

In order to testify the validity of the proposed method, we first conducted a computer simulation on a human knee joint motion assist system. Here, we assume that the human user
will generate periodic motion patterns by neural oscillators. Figure 7 shows our model of human-motion assist system, assuming that there are two joints at the knees, one is the human knee joint and the other is assist suit knee joint. Both knee joints are controlled by the neural oscillators, and the human leg and assist suit are bundled together.

![Figure 7 Models of assist system and human leg](image)

**A. Simulation method**

Figure 8 shows the entire image of the control method used in the simulation. This specific approach can be described as follows: firstly, mutual joint torque generated by interaction in the simulation. This specific approach can be described as mutual joint torque and these flows described above are repeated again and again to achieve a series of entrained and synchronized motions and these flows described above are repeated again and again to achieve a series of entrained and synchronized motions between the human user and the assist suit.

![Figure 8 Models of simulation method](image)

**B. Dynamic equations of system**

Dynamic equation of this system is written by

\[
\tau = \begin{pmatrix}
\tau_{1x} \\
\tau_{1y}
\end{pmatrix} = \begin{pmatrix}
M_x \ddot{\theta}_x + k_1 (\dot{\theta}_x - \dot{\theta}_a) + k_2 (\theta_x - \theta_a) \\
M_y \ddot{\theta}_y - k_1 (\dot{\theta}_y - \dot{\theta}_a) - k_2 (\theta_y - \theta_a)
\end{pmatrix}
\]  

(7)

\(M_x, M_y\) are the inertial moment, \(k_1 (\dot{\theta}_x - \dot{\theta}_a) + k_2 (\theta_x - \theta_a)\) is the constraint force term between human and assist suit, \(k_1\) is proportion coefficients and \(k_2\) is viscous coefficients. By using the vectors, equation (7) can be represented as the following equation.

\[
s = Ax + B\tau
\]  

(8)

\[
A = \begin{pmatrix}
0 & 1 & 0 & 0 \\
\frac{k_1}{M_x} & \frac{k_2}{M_x} & \frac{k_1}{M_y} & \frac{k_2}{M_y} \\
0 & 0 & 0 & 1 \\
\frac{k_1}{M_a} & \frac{k_2}{M_a} & \frac{k_1}{M_a} & \frac{k_2}{M_a}
\end{pmatrix}
\]  

(9)

**TABLE I**

<table>
<thead>
<tr>
<th>(k_1) (Nm/rad)</th>
<th>(k_2) (Nm s/rad)</th>
<th>(k_p) (Nm/rad)</th>
<th>(k_d) (Nm s/rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>5</td>
<td>100</td>
<td>5</td>
</tr>
</tbody>
</table>

**TABLE II**

<table>
<thead>
<tr>
<th>LINK PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>(M_h) (kg m²)</td>
</tr>
<tr>
<td>(M_a) (kg m²)</td>
</tr>
</tbody>
</table>

**C. Simulation results**

For \(T_r, T_a\) belongs to equation (4)-(6), here we determine \(T_r\) by 0.12 and \(T_a\) by 0.6 for assist suit, \(T_r\) by 0.16 and \(T_a\) by 0.8 for human. Consequently, the basic frequencies of the robot and human user are determined to be 1Hz and 0.7Hz, respectively. Figure 9 shows an example of independent torque and motion of for suit and the leg acting independently. The upper part of Fig. 9 shows the torque of the human user has a very small amount of force so that this person himself cannot be expected to make any locomotion. In other words,

\[
B^T = \begin{pmatrix}
0 & 1 & 0 & 0 \\
0 & 0 & 0 & 1
\end{pmatrix}
\]  

(10)

\(\tau\) is going to be defined by local feedback control as showed in equation (11). \(k_1\) is the proportional gain, \(k_d\) is the differential gain. In addition, \(\Theta_d\) is the desired angle output by the neural oscillator.

\[
\tau = \begin{pmatrix}
\tau_{1x} \\
\tau_{1y}
\end{pmatrix} = \begin{pmatrix}
k_1 (\dot{\theta}_x - \dot{\theta}_a) + k_2 (\theta_x - \theta_a) \\
k_1 (\dot{\theta}_y - \dot{\theta}_a) + k_2 (\theta_y - \theta_a)
\end{pmatrix}
\]  

(11)

Equation (8) is integrated by the Runge-Kutta method. The values of parameters are listed in Table I. The values of links’ parameters used in this simulation are listed in Table II.

![Figure 9 Original oscillations](image)

![Figure 10 Torque of robot when make independent oscillations](image)
he is willing yet unable to move his leg by his own torque of 0.3 Nm, even though just in a lower frequency of 0.7 Hz than that of the assist suit. This person may not be optimistic about his physical strength if he is not being assisted. On the other hand, the lower part of Fig. 9 shows the angle of the assist suit, which can move its leg link at a frequency of 1.0 Hz and at an amplitude of about 0.4 rad. Consequently, about 6 Nm amounts of torque shown in Fig. 10 originates from the assist suit’s locomotion mentioned above.

We conducted a series of simulations on this human-assist suit system based on SBC. Next we will discuss the simulation results.

1) Synchronization action

Figure 11 shows synchronized motions of assist suit and human legs in combination using SBC. Here, constraint force coefficients $k_1$ and $k_2$ are determined to be 100.0 and 5.0 respectively. Each synchronization gain of the human user and the assist suit is represented by $C_h$ and $C_a$. Figure 11(a) shows synchronized motions when $C_h = 0.0$ and $C_a = 0.1$, that is to say, the human user keeps his own frequency actively and assist suit’s motion is entrained and synchronized with that of the human user. It can be seen from Fig. 11 (a) that the frequency of synchronized motion is 0.7Hz as desired, and the human user is able to move at an amplitude of nearly 1.0 rad.

We investigated the changes brought about by the synchronization gain. Figure 11 (b) shows both real angles of the human user and the assist suit when $C_h$ is determined by 0.1 and $C_a$ is determined by 0.0. That is to say, the assist suit keeps its own frequency and amplitude actively and the user’s motion is entrained and synchronized with that of the assist suit. We found that the frequency of the synchronized motion changes to 1.0 Hz. Figure 11 (c) shows both real angles of the user and the assist suit when $C_h$ is determined to be 0.1 and $C_a$ is determined to be 0.04. Both assist suit and human are actively willing to inhibit their movement to a certain extent, as both of their motions are going to be entrained and synchronized. It is shown by Fig. 11 (c) that the frequency of synchronized motion changes to 0.85Hz.

In addition, we conducted a simulation where we kept the human user’s synchronization gain $C_h$ at 0 but increased the assist suit’s synchronization gain to 0.01, 0.04 and 0.1, then we make investigations on the change of mutual torque under each conditions. The relationship of average value of mutual torque and synchronization gain is shown in figure 12. We found that the mutual torque decreases as synchronization gain increases. Therefore, we conclude that because the synchronization motion between the human user and the assist suit has been realized, the mutual torque decreased. In other words, the synchronization has been evidenced by the simulation.

2) Assist effect

Figure 13 shows the torques generated in different situations. The upper part of Fig. 13 shows the torque of the human user with movement independently and together with assist suit respectively. When a human user moves by himself, he can just put forth physical effort about 0.3Nm, which is too small to make any locomotion, shown by the solid line in the upper part of Fig. 13, but when combined with the assist suit,
he can make such a locomotion at an amplitude of nearly 1.0 rad with the help of the assist suit which is shown by the dotted line in the upper part of Fig. 13. This shows how the human user’s physical strength has been augmented by the assist suit.

From simulation results, it can be concluded that not only human’s physical strength has been augmented by the assist suit, but also three kinds of synchronization motion (active, passive, as well as between active and passive) can be realized with SBC using a neural oscillator. In other words, it can be thought as assist suit has an acceptable level of usability for the user.

IV. EXPERIMENT

The proposed framework using neural oscillators is examined by experiments of a human-robot knee joint assisted movement. In this section we will describe experimentations including experimental method, devices and evaluation of experiment results.

A. Experimental method

The experimental control method is proposed as follows: firstly, mutual joint torque generated by interaction and joint angle is measured with a torque sensor and encoder, respectively. Mutual joint torque will be used as the input signals for neural oscillators, and synchronized output signals of neural oscillators will be used as desired angle of robot joint. Then PD feedback control is performed to determine the real angle of the robot joint. The specific flow is shown in Fig. 14.

B. Experimental equipment and control system

As can be seen in Fig. 15 this 1 degree of freedom system consists of two links and one actuator FHA-17C-50-E250 provided by Harmonic Drive Systems Company. This actuator has a built-in joint torque sensor. The torque sensing technique utilizes a flexible harmonic drive gear, which not only allows joint torque sensing without reducing stiffness of robot but also compacts the structure of the joint [10][11]. Once an external force is applied, the mutual joint torque will be measured. ART-Linux is used for this control system. Its overview has been showed in Fig. 17.

C. Experimental results

A series of experiments has been conducted to verify the results from the simulation. In the experiment, the assist suit is also determined to move at a frequency of 1.0 Hz and at an amplitude of 20.0 deg. We use a band to bind the user’s leg and the assist suit tightly together as shown in Fig. 16. The subject, a university student, was asked to keep a basic frequency of about 0.8Hz by listening to a metronome. In the experiment, we know it is difficult to determine the synchronization level of human by assigning a fixed value, nonetheless we defined human synchronization as follows: no synchronization, little synchronization and high synchronization are represented by A, B, C respectively.

1) Synchronization action

![Fig. 14 Models of experimental method](image)

![Fig. 15 Models of experimental robot leg](image)

![Fig. 16 overview of experiment](image)

![Fig. 17 Overview of control system](image)

![Fig. 18 Angles of human and assist suit](image)
First, we investigated the motion patterns when each synchronization gain changes. The result is shown in Fig. 18. In the case of $C_h=A$, $C_a=0.28$ (Fig.18 (a)), human moves actively but assist suit moves passively, consequently the motion of whole system changes to the human user’s basic frequency of 0.81Hz. On the other hand, Figure 18 (b) shows the result of $C_h=C$, $C_a=0.0$, where the human user is very passive and adapts himself to the motion of the assist suit. We further investigated in the case of $C_h=B$, $C_a=0.14$ shown in Fig. 18 (c), both the human user and the assist suit are willing to keep their intentions active to some extent, but finally have to come to a compromise so that both of their motions are synchronized and move at a middle frequency of 0.85 Hz.

Second, the subject was asked to move at his own pace arbitrarily ($C_h=A$), but the assist suit’s synchronization gain was increased to 0.14, 0.28, 0.43 respectively. We investigated the change of mutual torque under each condition. The relationship of mutual torque and synchronization gain is shown in Fig.19. We found that the results of the experiment matched those of the simulation.

2) Assist effect

We used a personal-EMG to measure muscle activity in five places in leg when human move independently and move together with assist suit. When human moves together with assist suit, the assist suit’s synchronization gain is determined to be 0.14. These results are shown in Fig.20. Muscle activity reaches 6.5% when the user moves together with the assist suit, but it reaches 9.0% when the user moves by himself. So herein, it can be considered the assist effect has been verified. From the experimental results described above, we conclude that the human user’s physical strength has been augmented but also passive and active motion assist styles can be realized by adjusting the value of synchronization gain. That is to say, SBC provides an acceptable level of usability for the user.

V. CONCLUSION

We proposed a framework for a synchronization based controller (SBC) using neural oscillators for motion assist. This control scheme has one superior characteristic: motion assist styles (Passive, active and between passive and active) can be realized by adjusting the strength of the synchronization, which means to be facilitated in operation. We examined the validity and feasibility of proposed method by conducting computer simulations on a human-assist system and experiments with a built-in joint torque sensor robot suit. From the results, we can concluded the following: by using SBC, firstly, the synchronization motion can be realized; secondly, the motion assist effect has been obtained; finally, motion styles can be adjusted. From above, it can be concluded SBC is a useful control method for motion assist.

In future research, we will conduct a psychological evaluation for this proposed method comparing it to other control methods. After that, we will focus on applying SBC on a multi-DOF motion assist suit. While neural oscillators just can be applied to periodic motions, we are also conducting research on their application to non-periodic motion [12].

REFERENCES