Communications in Information and Systems
Volume 22, Number 4, 499–526, 2022

ZMP-based fall prevention assist for lower-limb exoskeletons during dynamic walking

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A lower-limb power-assist exoskeleton robot is a wearable device that assists persons in their daily activities. Although the main purpose of the lower-limb exoskeleton robot is to assist the intended motion of the user, the stability of the robot's posture is still one of the biggest challenges. This paper focuses on the balance aspect of the exoskeleton robot in terms of control considering Zero Moment Point (ZMP) that is widely used in biped robots. A ZMP based fall prevention assist method, that prevents the user from falling down by giving equivalent external motion modification force to the user during dynamic walking on even terrains, is proposed in this paper. Fall prevention assist strategy is changed between a double support phase and a single support phase in the proposed method. Position of swing leg, velocity of swing leg, and change rate of ZMP are considered as an index to stabilize the posture of the exoskeleton during dynamic walking in the proposed method. In the proposed method, fuzzy control approach is applied to keep the ZMP inside the support polygon by generating the equivalent motion modification force at the chest or back of the user by the lower-limb exoskeleton for fall prevention assist during walking without making additional steps. The effectiveness of the proposed method is evaluated through experiments.

1. Introduction

Due to the decline in motor function, physically weak people such as elderly persons, disabled persons, or injured persons face difficulties in their daily task activities and they need constant assistance. One of the solutions to provide them independent life is to use a power-assist exoskeleton robot which can be used in various fields such as agriculture, industry, medicine, etc. There have been many studies on the power-assist exoskeleton robots [1–15] Q. Chen, *et al.*, that focus on hardware, motion intention estimation of the user, or trajectory generation aspects of the exoskeleton robot. Even though the main purpose of the exoskeleton robot is to generate the intended motion of the user, the stability of the exoskeleton's posture plays a key role in the lower-limb power-assist exoskeleton for daily motion assist. Unlike a humanoid robot which is able to move considering its own stability, the lower-limb power-assist exoskeleton robot must move according to the motion intention of the user. Therefore, the stability of the motion is not considered by the exoskeleton robot unless the user tries to move considering the motion stability. Although some studies focused on the balance aspect of the lower-limb exoskeleton robot [10, 13, 15–20], the stability of the posture is still one of the biggest challenges in the development process of the lower-limb exoskeleton robot.

Some exoskeletons provide crutches to users to solve the balance problem [8, 15, 22, 23]. Although the crutches might increase the stability, they might restrict the freedom of the hands' motions and there is a possibility of falling backward if they are not controlled properly. Moreover, the crutches require certain amount of upper-body strength, that might be problematic for people with weakened muscles. Li *et al.* proposed a method to use balance stabilizer mechanism [17] instead of crutches and canes. The stabilizer is attached to the hardware of the exoskeleton and it is activated by the exoskeleton robot automatically, although the exoskeleton with attached balance stabilizer is not mobile and it requires certain space on coronal plane. Another powered exoskeleton Mindwalker with balance assist [18] prevents a user from falling sidewise. The fall prevention torque is applied to the hip joint (abduction/adduction) by adjusting the step width of the exoskeleton robot, so that a user does not fall sidewise. In both [17] and [18], trajectories of swing leg are predefined considering the balance parameters of the exoskeleton robot, so that the posture of a user wearing the exoskeleton robot is stable during a swing motion. However, the predefined trajectories cannot cope with unexpected disturbances such as bumps or applied external forces. Therefore, these methods are not practical for dynamic walking and they cannot be applied for non-predefined types of power-assist methods such as [13] that uses EMG (Electromyogram) for trajectory generation of the lower-limb exoskeleton robot. To solve this problem, Zha *et al.* [19] proposed a method for single-step balance recovery during dynamic walking with non-predefined trajectory of swing leg, although the application is limited to the exoskeleton robot which consists of only one active joint at the hip. The absence of an active ankle joint (dorsi/plantar flexion) limits the adaptability of their method during dynamic walking, since the ankle joint of the stance leg hugely affects the posture of the user regarding to his/her balance. Ugurly *et al.* [20] proposed a balance controller for the exoskeleton robot by using variable physical stiffness at the ankle joint and evaluated its effectiveness with a bipedal robot during static motion.

This paper proposes a fall prevention assist method during dynamic walking in accordance with the user's motion intention using a 6-DOF (6 degrees of freedom) lower-limb exoskeleton robot. Walking motion consists of two phases: a double support phase (DSP) and a single support phase (SSP). The user's body weight is supported by one stance leg in the SSP and the user's body weight is supported by both legs in the DSP. During the DSP, the support polygon created by both legs is relatively large. On the other hand, one leg is in dynamic phase, and the support polygon is small during the SSP. Since the difference between two phases is significant, the strategies for fall prevention vary from each other. Fall prevention assist for the DSP is less challenging and the basic idea was already proposed by Kiguchi *et al.* [13] as described at §4. In that study, ZMP (Zero Moment Point) [24], which is one of the most important indices to evaluate the walking stability, was the parameter used for fall prevention assist during the DSP, by keeping ZMP inside the support polygon. For the SSP, however, another parameter must be taken into account in addition to ZMP to evaluate the stability condition of the exoskeleton. By knowing three parameters such as the change rate of ZMP, position of swing leg, and velocity of swing leg, the stability condition of the exoskeleton worn by a user is evaluated and the necessity to apply the proposed fall prevention can be decided. In this study, fuzzy control approach is proposed to keep ZMP inside the support polygon by generating the posture modification force which is equivalently applied to the user's upper-body by the lower-limb exoskeleton robot for fall prevention assist during the SSP. Three parameters mentioned above are used as inputs to evaluate the stability condition of the exoskeleton and the posture modification force which is equivalently applied to the user's upper-body by the lower-limb exoskeleton robot is defined as the output of the fuzzy controller. When the posture of the exoskeleton worn by a user is going to be unstable, the required posture modification force is generated in added to the power-assist torque which is required to assist the user's intended motion. The output (*i.e.*, the posture modification force) of the proposed method is realized by generating additional torques to hip (flexion/extension), knee (flexion/extension), and ankle (dorsi/plantar flexion) joints of the stance leg of the exoskeleton robot to prevent a user from falling forward or backward without making additional steps of the user. The proposed fall prevention assist method is simple but effective, especially when additional steps of the user are not allowed by the surrounding environment. Note that the proposed fall prevention assist method is applied only when

Table 1: Comparison of human's and robot's range of motion

Joint motion		Human [deg]	Exoskeleton robot [deg]
Hip	Flexion	130	120
	Extension	30	20
Knee	Flexion	140	110
	Extension	0	0
Ankle	Flexion	30	20
	Extension	50	50

the user's reaction force is not enough to stabilize and the fall prevention assist is necessary for the exoskeleton. The effectiveness of the proposed method is evaluated by performing experiments.

2. Lower-limb exoskeleton used in this study

Figure 1 shows the lower-limb power-assist exoskeleton robot that is used in this study. The exoskeleton robot has three active DOFs, *i.e.* hip (flexion/extension), knee (flexion/extension) and ankle (dorsi/plantar flexion) joints in each leg. The active joints are controlled with attached DC motors that assist robot's motion in sagittal plane. Table 1 describes the average movable range of motion of human's leg and the movable range of motion of the exoskeleton robot used in this study.

The exoskeleton also consists of rotatory encoders, laser range finders, links, force sensors, tactile switches and foot holders. The rotatory encoders are attached to the DC motors and measure angles of leg joints. The tactile switches are attached to the sole part of the exoskeleton and can detect whether the foot of the exoskeleton robot touched the ground or not. To determine the motion difference between the exoskeleton robot and a user, 3-axis force sensors are attached between the frames and the holders. Force sensors are also attached to the chest and the back of exoskeleton robot to determine external push force in the experiment.

The exoskeleton is basically controlled to assist the user's lower-limb motion based on the user's motion intention that is detected based on the user's EMG signals to realize effective power-assist [14]. However, force-sensor-based control is applied to follow the user's motion in this study to exclude the effect of power-assist and see the effect of proposed fall prevention method only.

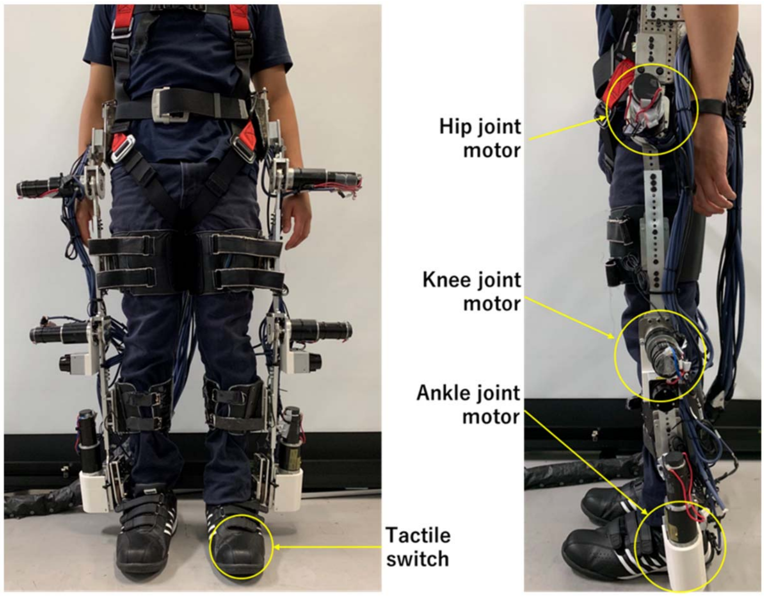


Figure 1: Lower-limb power-assist exoskeleton robot.

3. ZMP and stability

ZMP is the main criteria related to the stability of bipedal robots. It represents as a point on the ground where all dynamic forces acting at the contact foot do not produce any moment [25]. It is mainly used in humanoid robots for stable biped locomotion and there are several strategies to generate bipedal motion using ZMP criteria [26–32]. Since properties of the lower-limb exoskeleton robot are similar to those of the humanoid robot, ZMP criteria can be used in the exoskeleton for stable motion as well [21], although the exoskeleton robot is mainly activated to assist the intended motion of the user and the dynamics of the user affects the dynamics of the exoskeleton robot also. During the SSP of human walking, the trajectory of ZMP travels from the heel to the toe. Whereas, during DSP, the position of ZMP shifts from the previous stance leg to the next stance leg.

3.1. Calculation of ZMP

In this study, ZMP of the user with the exoskeleton robot plays an essential role in determining the balance of the exoskeleton robot worn by the user during dynamic walking. It is represented as the point on the ground (floor)

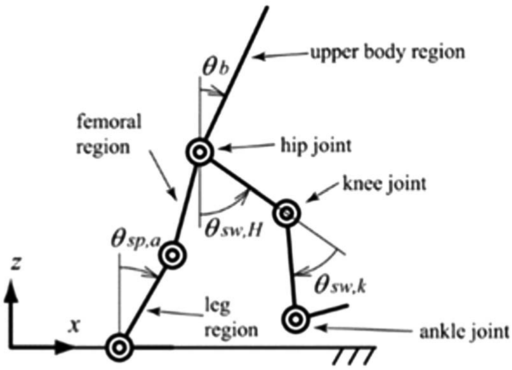


Figure 2: Robot posture.

and can be calculated based on information of the position and the posture of the exoskeleton robot based on the model shown in Fig. 2. Since the encoders can detect angle of each joint around y-axis only, the position and the posture of the exoskeleton robot can be calculated in the sagittal plane. The origin of the coordinate system is located at the ankle joint of the support leg, and the support leg can be detected by the tactile switches located at soles of the exoskeleton robot.

After the position of each link is calculated, ZMP of the user with the exoskeleton robot can be calculated based on the following formula:

$$x_{\text{ZMP}} = \frac{\sum_{i=1}^{n} m_i(\ddot{z}_i + g)x_i - \sum_{i=1}^{n} m_i \ddot{x}_i z_i}{\sum_{i=1}^{n} m_i(\ddot{z}_i + g)} \tag{1}$$

where x_{ZMP} is the position of ZMP in x-axis, m_i is the combined mass of each human body part and the corresponding link of exoskeleton robot, and x_i and z_i are the positions of the center of gravity (COG) of each human body part and the corresponding link of the exoskeleton robot. By knowing the height and the weight of the user, the mass and the COG position of each body part of the user can be estimated [33].

Figure 3 shows an example of ZMP behavior during one gait cycle when a person wearing the exoskeleton robot walks. In this figure, one can see that ZMP stayed inside the support polygon area.

3.2. Stability of robot posture

The support polygon is the area created by all contact points of the robot and the ground. Figure 4(a) shows the support polygon formed in the DSP

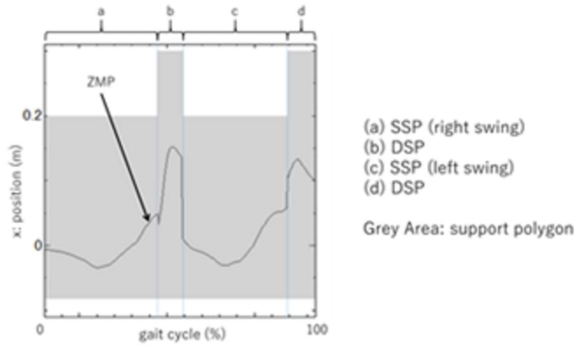


Figure 3: Behavior of ZMP during one gait cycle.

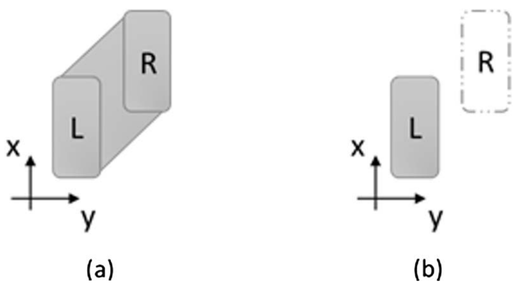


Figure 4: Support polygon.

and Fig. 4(b) shows that formed in the SSP. These figures show the sole of the robot in x and y-axis, and the grey area represents support polygon that is also known as the safe region. When ZMP is located inside the support polygon area, the posture is stable and when ZMP is located outside the support polygon area, the posture is unstable, and then the robot loses the balance. Keeping ZMP inside the support polygon would ensure the stability of the robot posture.

4. Fall prevention assist for DSP

The fall prevention assist for the DSP was proposed in [13] and the idea is to always keep ZMP inside support polygon. As shown in Fig 5, when ZMP is located near the edge of the support polygon, additional torque is applied to the joints to push ZMP back to the center of support polygon. However, when ZMP is located around the center of support polygon, no additional torque is applied. The assist torque for fall prevention in Fig. 5

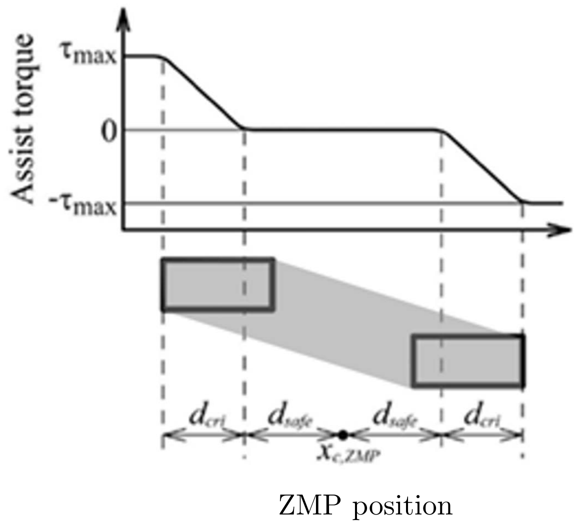


Figure 5: Fall prevention assist for DSP.

can be described in Eq. (2).

$$(2) \quad \tau_{\text{walk}} = \begin{cases} 0, & (|\Delta x_{\text{ZMP}}| < d_{\text{safe}}) \\ \frac{\tau_{\max}}{d_{\text{cri}}}(\Delta x_{\text{ZMP}} - S_{\text{gn}} d_{\text{safe}}), & (d_{\text{safe}} \leq |\Delta x_{\text{ZMP}}| < d_{\text{safe}} + d_{\text{cri}}) \\ S_{\text{gn}} \tau_{\max}, & |\Delta x_{\text{ZMP}}| \geq d_{\text{safe}} + d_{\text{cri}}) \end{cases}$$

$$\Delta x_{\text{ZMP}} = x_{\text{c,ZMP}} - x_{\text{ZMP}}$$
$$S_{\text{gn}} = \text{sgn}(\Delta x_{\text{ZMP}})$$

where $x_{\text{c,ZMP}}$ is the center of support polygon, and d_{cri} and d_{safe} are distances shown in Fig. 5. Here, d_{cri}, d_{safe} and $\tau_{\max}$ are experimentally obtained.

5. Fall prevention assist for SSP

In the SSP, the support polygon is the area created by the sole of support leg only, as shown in Fig. 4(b). When the exoskeleton robot loses its balance, ZMP leaves the support leg, *i.e.*, the support polygon. If the balance is lost, the falling motion would be induced. As the swing leg lands on the ground, the larger support polygon area would be created and there is a chance that ZMP might be located inside the new support polygon. Therefore, the

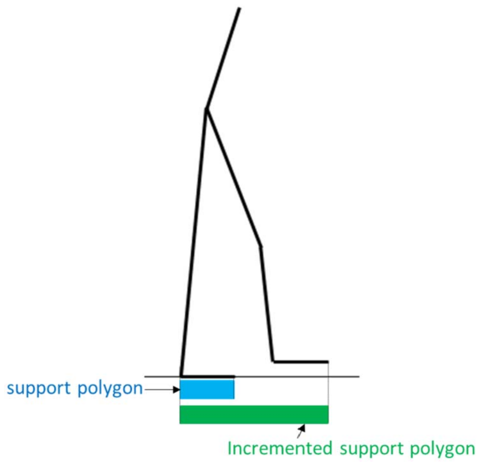


Figure 6: Incremented support polygon (ISP).

exoskeleton robot might regain its posture stability. For convenience, the potential support polygon that might be created due to loss of balance is referred as Incremented Support Polygon (ISP) in this paper. As shown in Fig. 6, ISP is the area created on the ground by both stance leg and hovering swing leg. The main idea of the proposed method is to keep ZMP inside the ISP during SSP by giving the equivalent motion modification force at the chest or back of the user by the lower-limb exoskeleton robot.

To make the proposed idea clearer, an example case is shown in Fig. 7. In Fig. 7(a), ZMP is located inside the support polygon, and the swing leg is moving forward. Then, at some point of this swing phase, ZMP moves forward slowly and eventually goes out of the support polygon as shown in Fig. 7(b), but stays inside the ISP. As the robot user starts to lose balance, the swing leg will eventually land on the ground so that the area of support polygon increases and ZMP will be located inside support polygon again as shown in Fig. 7(c). Therefore, applying balance control is not necessary in this case.

Another similar case is shown in Fig. 8. Here, ZMP moves forward with much higher speed, meaning that the change rate of ZMP is high. As ZMP moves forward fast, it goes out of both conventional support polygon and ISP at some point as shown in Fig. 8(b). Therefore, the robot user loses balance even after the swing leg lands on the ground. Since change rate of ZMP is very fast, ZMP will be located outside of the support polygon created by both legs by the time the swing leg lands on the ground. Therefore, applying

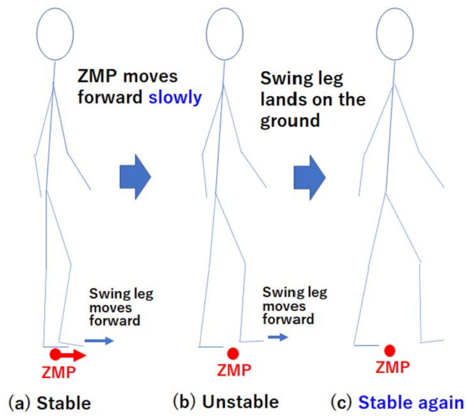


Figure 7: Example 1 (fall prevention is not required).

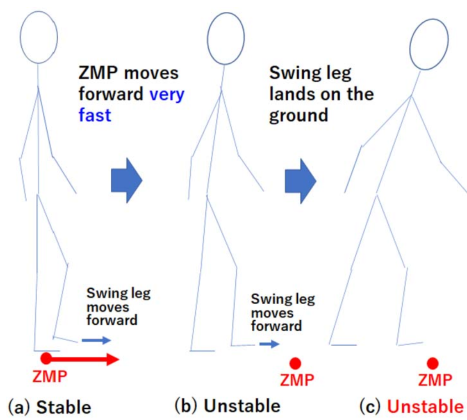


Figure 8: Example 2 (fall prevention is not required).

balance control is necessary in this case to prevent falling down accident. The fuzzy if-then rule for this example case would be the following: "If the *position of swing leg* is in front of stance leg, AND the *velocity of swing leg* is moving forward, AND if *change rate of ZMP* is moving forward with high speed, fall prevention assist in *negative* direction is necessary". Here, negative output means to push ZMP backwards to the negative direction by applying equivalent modification force to the user's upper-body with the lower-limb exoskeleton. The method to apply equivalent modification force to the joints of the stance leg is described at this chapter in §5.2.

As it was described by the examples above, considering the change rate of ZMP is an important index to prevent a user from a rapid loss of balance. If the change rate of ZMP is faster, then more torque is required to prevent a user from falling down. Therefore, the change rate of ZMP is selected as the one of the inputs for fuzzy control. The degree of the ZMP's change rate (*i.e.*, how fast the change rate of ZMP occurs) is not constant and it is a function of the position of ZMP and ISP.

In order to keep ZMP inside ISP by using the fall prevention assist, it is also important to know the location of ISP. Since ISP is basically the area created by the swing and stance legs, the position of the swing leg relative to the position of stance should be known. Consequently, it is used as the second input of the fuzzy control.

In order to keep ZMP inside the shrinking ISP, it is important to apply fall prevention assist to push ZMP towards the direction where ISP has been shrunk. Since the change of the ISP's shape is directly related to the velocity of the swing leg, it is also important to keep track of the velocity of swing leg. Therefore, the velocity of the swing leg is used as the third input of fuzzy control. The output from the fuzzy control is the force which is equivalently applied to the user's upper-body by the lower-limb exoskeleton to control the location of ZMP in order to stabilize the balance.

In summary, ZMP is always kept inside the ISP considering three parameters: change rate of ZMP, position of swing leg, and the velocity of the swing leg. The output from the fuzzy control is the force equivalently applied to the user's upper-body by the lower-limb exoskeleton to control the location of ZMP.

5.1. Fuzzy control rules and fuzzy sets

Fuzzy control rules are defined for the purpose of keeping ZMP inside the ISP, similar to the cases shown in Figs. 7 and 8. Three fuzzy sets (Negative, Zero, and Positive) are defined for the control output, *i.e.*, force equivalently applied to the user's upper-body. For three inputs: position of swing leg (input 1), velocity of swing leg (input 2), and change rate of ZMP (input 3), three (behind, same, and ahead), three (backward, static, and forward), and five (Negative Big, Negative Small, Point Zero, Positive Small, and Positive Big) fuzzy sets are prepared, respectively. Therefore, the possible combination of all inputs would be $3 \times 3 \times 5 = 45$. Consequently, 45 fuzzy if-then rules are defined as shown in Fig. 9. The order of rules is defined from up to down and from left to right:

Rule 1 If "position of swing leg" is behind, AND "velocity of swing leg" is backward, AND "change rate of ZMP" is NB, then output torque is Positive;

IF Position of swing leg is **behind of stance** leg AND...

	Change rate of ZMP				
Velocity	NB	NS	PZ	PS	PB
Backward	Positive	Zero	Zero	Negative	Negative
Static	Positive	Zero	Zero	Negative	Negative
Forward	Positive	Zero	Zero	Negative	Negative

IF Position of swing leg is **same** as stance leg AND...

	Change rate of ZMP				
Velocity	NB	NS	PZ	PS	PB
Backward	Positive	Zero	Zero	Negative	Negative
Static	Positive	Positive	Zero	Negative	Negative
Forward	Positive	Positive	Zero	Zero	Negative

IF Position of swing leg is **ahead of stance** leg AND...

	Change rate of ZMP				
Velocity	NB	NS	PZ	PS	PB
Backward	Positive	Positive	Zero	Zero	Negative
Static	Positive	Positive	Zero	Zero	Negative
Forward	Positive	Positive	Zero	Zero	Negative

Figure 9: Fuzzy rules.

Rule 2 If "position of swing leg" is behind, AND "velocity of swing leg" is backward, AND "change rate of ZMP" is NS, then output torque is Zero;

...

Rule 45 If "position of swing leg" is ahead, AND "velocity of swing leg" is forward, AND "change rate of ZMP" is PB, then output torque is Negative;

The example 1 (Fig. 7) and the example 2 (Fig. 8) described above are parts of these rules, representing the rule number 44 and the rule number 45, respectively.

Based on defined fuzzy rules, fuzzification process takes place. Based on the data taken with the exoskeleton robot, the degree of membership of each fuzzy set can be calculated. Degree of fitness of each rule is defined by multiplication of degrees of fitness of every input.

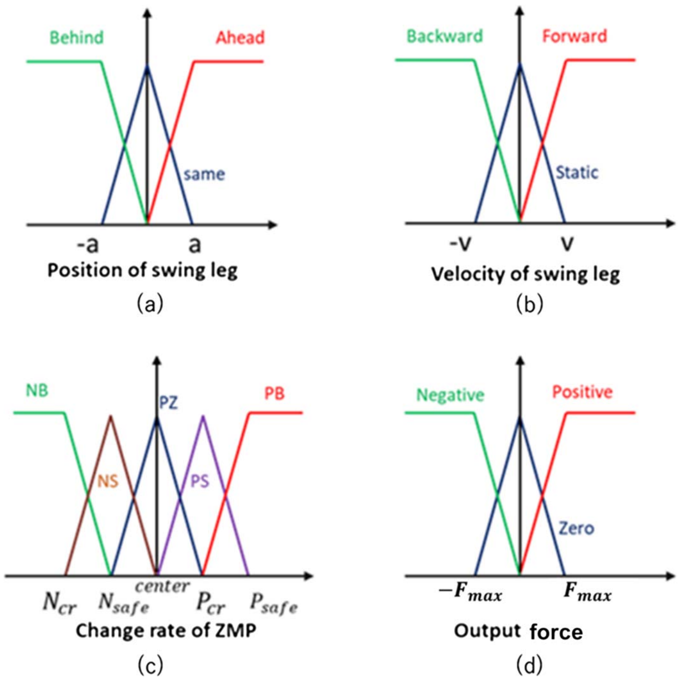


Figure 10: Membership functions.

5.2. Membership functions

Membership functions for fuzzy sets of each input and output are shown in Fig. 10, where x-axis represents the value of input or output, and y-axis represents the degree of fitness of each input, that varies between 0 and 1.

The first input (input 1) is Position of Swing Leg that has three fuzzy sets: behind, same and ahead. Its membership functions are shown in Fig. 10(a), where a is the length of sole of robot.

The second input (input 2) is Velocity of Swing Leg that has three fuzzy sets: backward, static and forward. The membership function for each fuzzy set is shown in Fig. 10(b), where v is the walking speed of the user, or the speed of treadmill.

The third input (input 3) is Change Rate of ZMP that has five fuzzy sets: Negative Big (NB), Negative Small (NS), Point Zero (PZ), Positive Small (PS), and Positive Big (PB). The membership function for each fuzzy set is shown in Fig. 10(c).

The formula for N_{cr}, N_{safe}, $center$, P_{safe} and P_{cr} in Fig. 10(c) can be obtained by the definition of the velocity that is ds/dt, where ds is the position difference between the actual position of ZMP and the border positions of ISP that can be defined in Fig. 11:

(3) $$N_{\text{cr}} = \frac{P_{\text{min}} - ZMP}{t_{\text{swing}} - t_{\text{passed}}}$$

(4) $$N_{\text{safe}} = \frac{P_{\text{min}} + offset - ZMP}{t_{\text{swing}} - t_{\text{passed}}}$$

(5) $$P_{\text{cr}} = \frac{P_{\text{max}} - ZMP}{t_{\text{swing}} - t_{\text{passed}}}$$

(6) $$P_{\text{safe}} = \frac{P_{\text{max}} - offset - ZMP}{t_{\text{swing}} - t_{\text{passed}}}$$

(7) $$Center = \frac{N_{\text{cr}} + P_{\text{cr}}}{2}$$

where P_{min} is the ankle base position of posterior leg in x-axis, P_{max} is the toe's tip position of anterior leg in x-axis. For additional safety, the offset from the edges of incremented support polygon was set at 10 mm. Also, ZMP is the position of x_{ZMP}, t_{passed} is the amount of time passed since

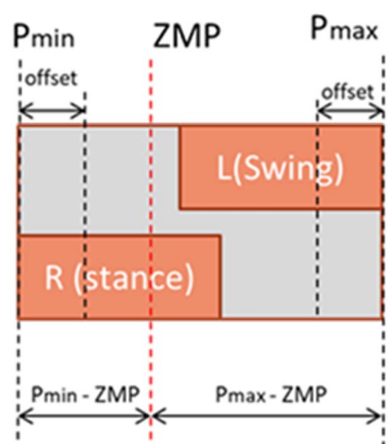


Figure 11: Border parameters of *incremented support polygon*.

the beginning of swing phase, and t_{swing} is expected time of swing phase. The relationship between the speed of treadmill and the duration of double stance phase is shown in [11]:

$$t_{\text{ds}} = 10^{\frac{0.405 - V_{\text{est}}}{0.908}} \tag{8}$$

where V_{est} is speed of treadmill.

In addition, the other study [32] suggests that the duration of double support phase is 24 % and the duration of swing phase is 76 % in one gait cycle. Therefore, the relationship between the durations of the DSP and the SSP is:

$$t_{\text{swing}} = \frac{76}{24} t_{\text{ds}} \tag{9}$$

By combining Eq. (8) and Eq. (9), the following relationship is obtained:

$$t_{\text{swing}} = \frac{76}{24} \cdot 10^{\frac{0.405 - V_{\text{est}}}{0.908}} \tag{10}$$

Finally, the output of fuzzy control (*i.e.*, the output force equivalently applied to user's upper-body to modify ZMP) is shown in Fig. 10(d). As shown in Fig. 12, by applying the force to the upper-body of user equivalently, position of ZMP can be modified. Here, Negative means to push ZMP to negative direction in x-axis and Positive means to push ZMP to positive direction in x-axis. Zero means that no force is required to modify ZMP. In Fig. 10(d), F_{max} is the maximum force required to prevent user from falling down. In this study, F_{max} is selected as the amount of external force that is needed to make the subject fall forward and backward, and it is obtained by Experiment 1 and Experiment 2 that are described in §6.

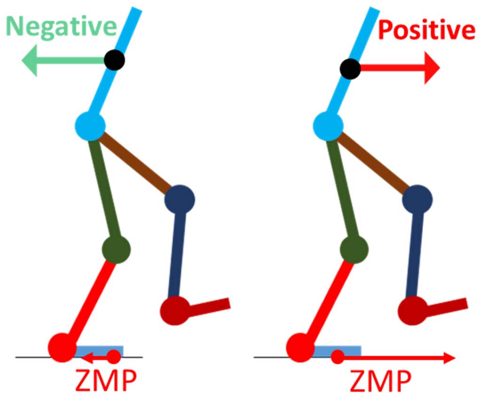
5.3. Defuzzification

In this study, the center of gravity method was applied for defuzzification. The formula for defuzzification is the following:

$$Fuzzy = \frac{a_1 b_1 c_1 u_1 + a_2 b_2 c_2 u_2 + \cdots + a_{45} b_{45} c_{45} u_{45}}{a_1 b_1 c_1 + a_2 b_2 c_2 + \cdots + a_{45} b_{45} c_{45}} \tag{11}$$

where u_n is real value of output defined in the consequent part of the simplified fuzzy control rule n as shown in x-axis of Fig. 10(d).

The equivalent motion modification force (*i.e.*, the output form the fuzzy control) is generated by applying torques to hip (flexion/extension), knee



(a) negative (b) positive

Figure 12: Definition of negative and positive of fuzzy output.

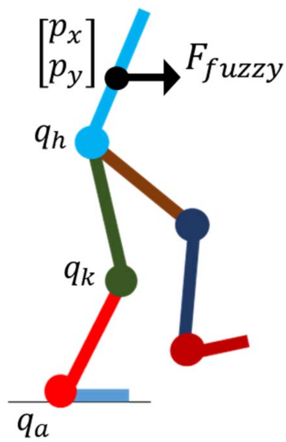
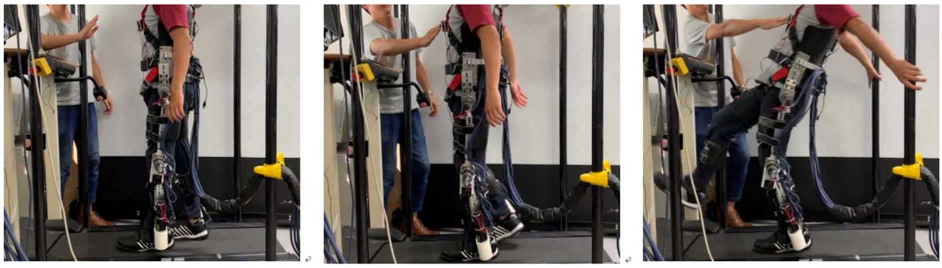


Figure 13: The method to generate fuzzy output force from joints of exoskeleton robot.

(flexion/extension), and ankle (dorsi/plantar flexion) joints of the stance leg of the exoskeleton robot as shown in Fig. 13 and calculated by using the following equation:

$$\begin{bmatrix} \tau_{\mathrm{h}} \\ \tau_{\mathrm{k}} \\ \tau_{\mathrm{a}} \end{bmatrix} = \begin{bmatrix} \frac{\partial p_x}{\partial q_{\mathrm{h}}} & \frac{\partial p_y}{\partial q_{\mathrm{h}}} \\ \frac{\partial p_x}{\partial q_{\mathrm{k}}} & \frac{\partial p_y}{\partial q_{\mathrm{k}}} \\ \frac{\partial p_x}{\partial q_{\mathrm{a}}} & \frac{\partial p_y}{\partial q_{\mathrm{a}}} \end{bmatrix} \begin{bmatrix} F_x \\ F_y \end{bmatrix} \tag{12}$$



(a) pre-swing state (b) occurrence of push (c) loss of balance

Figure 14: Experiment 1.

where p_x and p_y are the position of equivalently applied force by fuzzy control and q_h, q_k, q_a are joint angles of hip, knee, and ankle of stance leg, respectively. Since F_max is measured by force sensors, p_x and p_y are selected as the position of the force sensor. Since ZMP is controlled in x-axis only, $F_x = F_\mathrm{fuzzy}$, and $F_y = 0$.

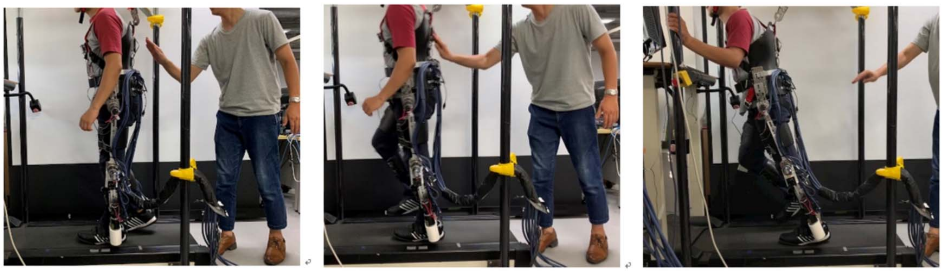
6. Experiment

The objective of the experiment is to prevent a subject wearing the exoskeleton robot from falling down during dynamic walking using the proposed method. In total four kinds of experiment were conducted to evaluate the effectiveness of the proposed method. Table 2 shows the overview of all four experiments.

In Experiment 1 (see Fig. 14) and Experiment 2 (see Fig. 15), the subject's chest and spine were pushed for the backward fall and the forward

Table 2: Overview of experiments

Experiment #	**Fall prevention assist**	**Direction of fall**	**Objective**
Experiment 1	Not applied	Backward	Measure the amount of force that is needed to make the subject fall down
Experiment 2	Not applied	Forward	
Experiment 3	Applied	Backward	Prevent the subject from falling down when the large enough pushes were applied
Experiment 4	Applied	Forward	



(a) pre-swing state (b) occurrence of push (c) loss of balance

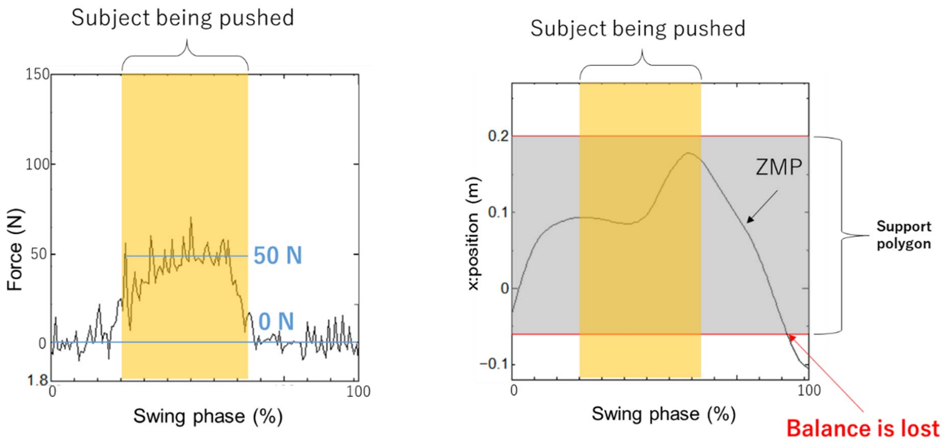
Figure 15: Experiment 2.

fall, respectively. The objective of Experiments 1 and 2 is to find out the amount of force that is needed to make the subject fall down during the SSP without the proposed method. The force sensors attached to the exoskeleton robot measure the amount of force applied from the both sides. In both Experiments 1 and 2, experiments were carried out several times with different amount of force to find out the required amount of force to make the subject fall down. In these two experiments, the proposed method for fall prevention assist is not applied.

In Experiments 3 and 4, the subject was pushed again from the chest for the backward fall and from the spine for the forward fall, respectively. However, the objective of Experiments 3 and 4 is to prevent the subject from falling down with the proposed method when the large enough push force was applied during the SSP. In order to make sure that pushes are strong enough, the amount of force that was applied for both pushes was more or equal to the required amount of force which was found out in Experiments 1 and 2 to make the subject fall down. In both Experiments 3 and 4, experiments were carried out several times. In all experiments, a person wearing the lower limb exoskeleton was asked to walk on a treadmill with the speed of 0.8 km/h. To prevent the subject to completely fall down, the harness of the exoskeleton was attached to the frame of the treadmill.

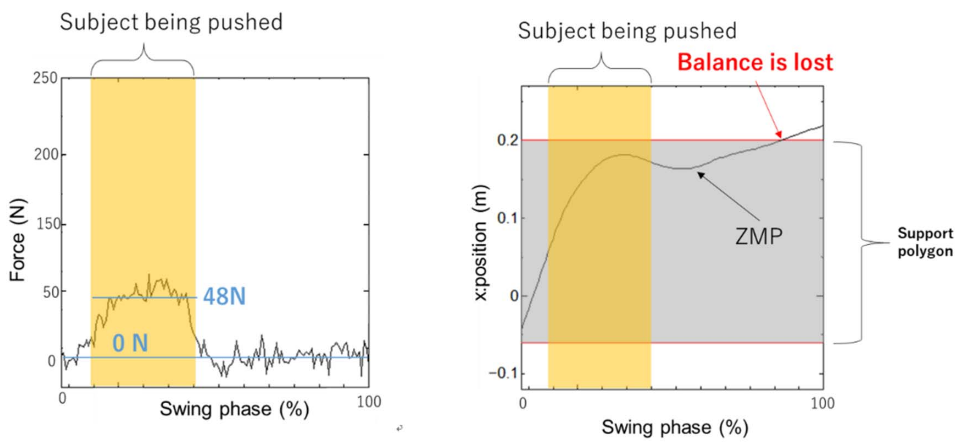
6.1. Results of experiment 1 and experiment 2

The results of Experiments 1 and 2 are shown in Fig. 16 and Fig. 17, respectively. Figures 16(a) and 17(a) show the amount of force that was applied to make the subject fall down by the pusher during the SSP and Figs. 16(b) and 17(b) show the behavior of ZMP during the same swing phase. Yellow area shows the duration of the push.



(a) applied force (b) behaviour of ZMP

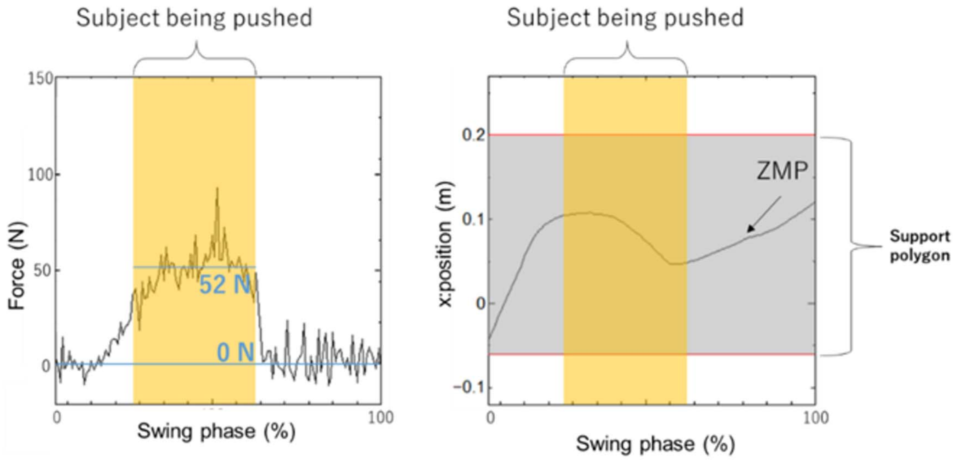
Figure 16: Results of experiment 1.



(a) applied force (b) behaviour of ZMP

Figure 17: Results of experiment 2.

In Experiment 1, when the subject was pushed backward by the applied force of 50 N, ZMP left the support polygon and then the subject lost his balance as shown in Fig. 16(a). Therefore, it was found out that the applied force of 50 N was enough to cause the subject to lose the balance backwards. In Experiment 2, when the subject was pushed forward by the applied force of 48 N, ZMP left the support polygon and then the subject lost his balance.



(a) applied force (b) behaviour of ZMP

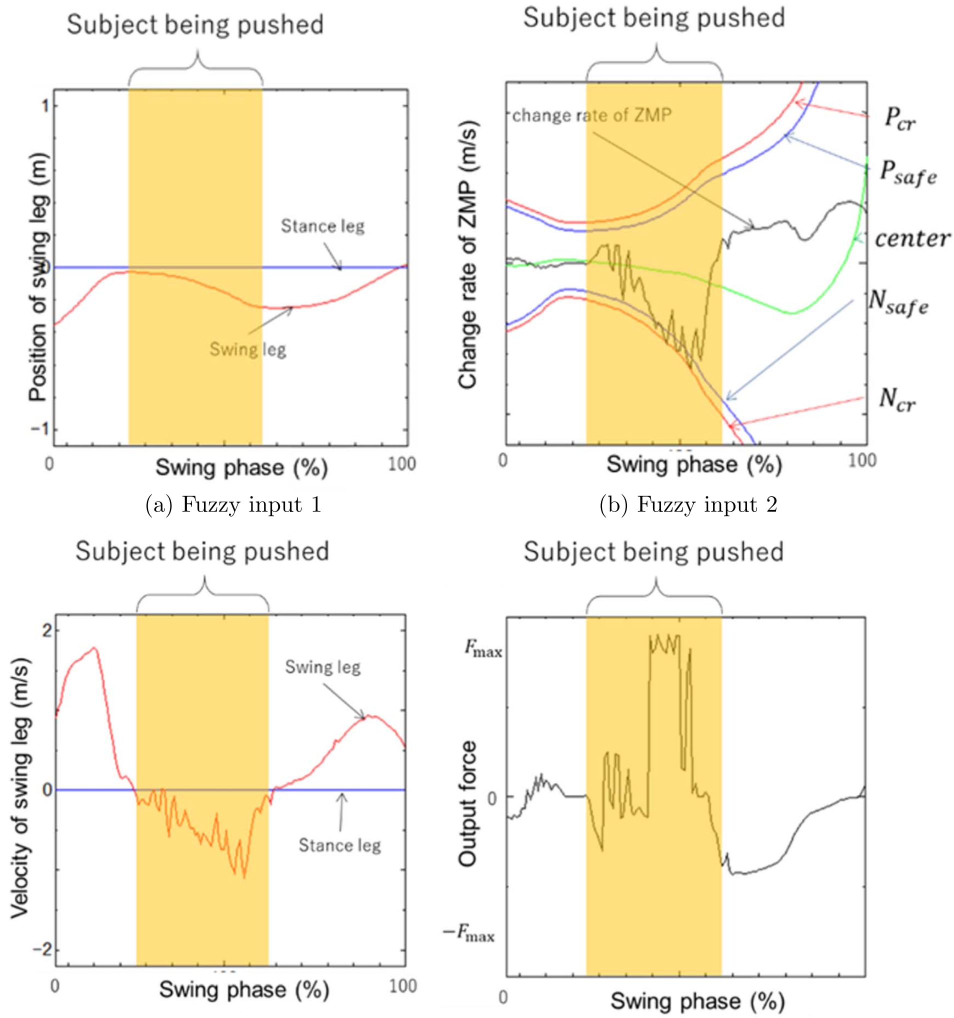
Figure 18: Results of experiment 3.

Therefore, it was found out that the applied force of 48 N was enough to cause the subject to lose the balance forwards.

6.2. Results of experiment 3 and experiment 4

Based on the results obtained in Experiments 1 and 2, the applied force of 50 N or larger was applied backward to the subject in Experiment 3 and the applied force of 48 N or larger was applied forward to the subject in Experiment 4. In Experiments 3 and 4, the subject was pushed from the chest and the back to make him fall down on purpose, respectively, as performed in Experiments 1 and 2. In order to see the effectiveness of the proposed method, the fall prevention assist method was applied in these experiments. Therefore, the subject will maintain his balance even though external disturbance force, which is strong enough to make the subject fall down, is applied during walking if the proposed method works effectively. The results of Experiment 3 are shown in Figs. 18 and 19, and those of Experiment 4 are shown in Figs. 20 and 21.

From Fig. 18(a), one can see that the amount of force of 52 N, which was larger than the force obtained in Experiment 1 to make the subject to fall down backward, was applied to the subject in Experiments 3. Although the results of Experiment 1 showed the subject could not maintain his balance even though he tried to recover from the external push force, Fig. 18(b)

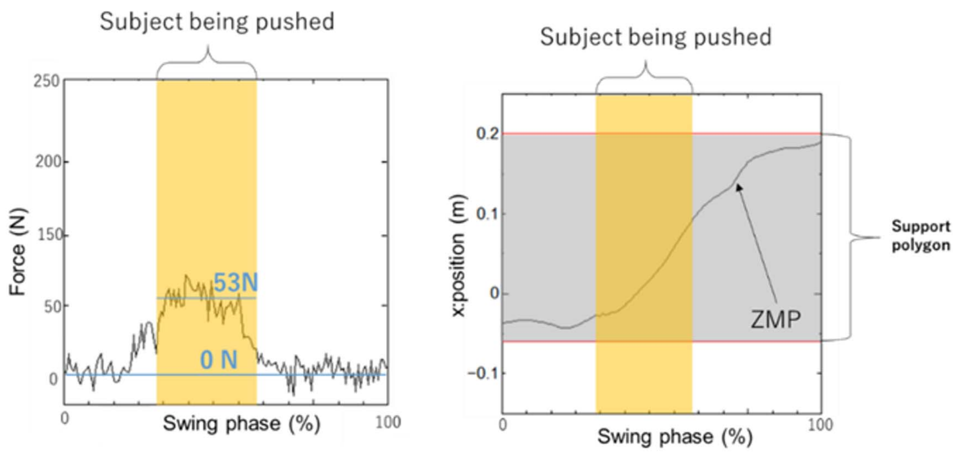


(a) Fuzzy input 1 (b) Fuzzy input 2

(c) Fuzzy input 3 (d) Fuzzy output 1

Figure 19: Fuzzy control during experiment 3.

shows that ZMP stayed inside the support polygon by the effect of the proposed method even though larger amount of push force was applied. Figure 19 shows the behavior of the fuzzy control when the external push force was applied. Fig. 19(a) shows the position of the swing and stance legs. Fig. 19(b) shows the change rate of ZMP, and the parameters of N_{cr}, N_{safe}, *center*, P_{safe} and P_{cr} in Fig. 10(c). Fig. 19(c) shows the velocity of the swing and stance legs. Furthermore, Fig. 19(d) shows the output force (*i.e.*, the



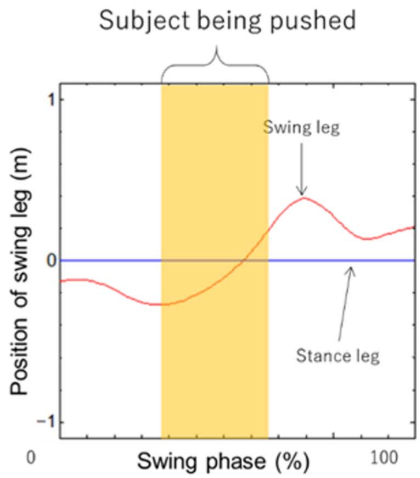
(a) applied force (b) behaviour of ZMP

Figure 20: Results of experiment 4.

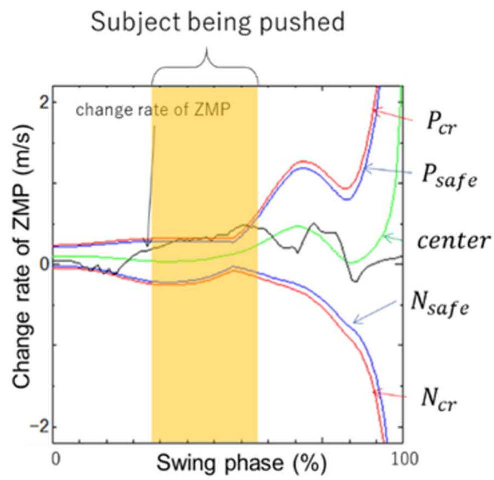
equivalent motion modification force) applied to the user by the exoskeleton robot using the proposed method to prevent the user from falling backward. As it can be observed, fuzzy controller reacted to the external backward push, by producing positive output equivalent force to push ZMP forward. The torque is applied to the joints of the stance leg as described in §5. The experiments were carried out several times and similar results were obtained in Experiment 3.

Similarly, from Fig. 20(a), one can see that the amount of force of 53 N, which was larger than the force obtained in Experiment 2 to make the subject to fall down forward, was applied to the subject in Experiments 4. Although the results of Experiment 2 showed the subject could not maintain his balance even though he tried to recover from the external push force, Fig. 20(b) shows that ZMP stayed inside the support polygon by the effect of the proposed method even though larger amount of push force was applied to the subject. Figure 21 shows the behavior of the fuzzy control when the external push force was applied. As it can be observed from Fig. 21(d), fuzzy controller reacted to the external backward push force by producing equivalent motion modification force in negative direction with the exoskeleton robot using the proposed method to push ZMP backward. The experiments were carried out several times and similar results were obtained in Experiment 4.

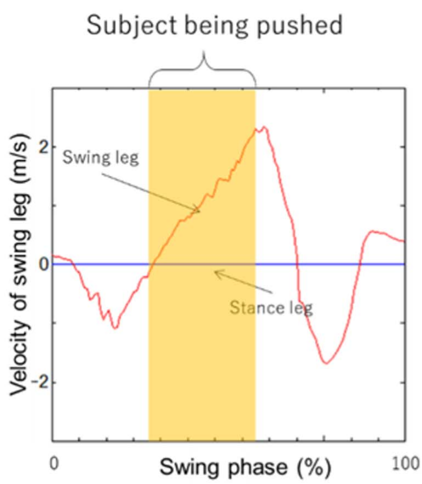
These experimental results show that the motion modification force is effectively generated with the proposed method to react to the external



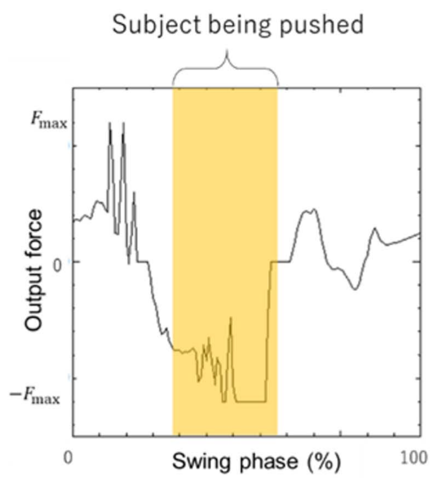
(a) Fuzzy input 1



(b) Fuzzy input 2



(c) Fuzzy input 3



(d) Fuzzy output 1

Figure 21: Fuzzy control during experiment 4.

disturbance (*i.e.*, push force) to prevent losing balance during the SSP.

7. Conclusion and future work

This paper proposed a method of fall prevention assist for the lower-limb power-assist exoskeleton robot during a dynamic walking. In the proposed method, the fall prevention assist force was estimated based on three parameters: change rate of ZMP, position of swing leg, and the velocity of the swing leg. These parameters were combined as the input of fuzzy control, and the equivalent motion modification force for fall prevention was generated with the defined fuzzy rules. The experimental results showed that the proposed method effectively prevented a user wearing the exoskeleton robot from falling forward and backward without making additional steps. The proposed fall prevention assist method is simple but effective, especially when additional steps are not allowed by the surrounding environment, although it can be combined with another approaches [35–37] if additional steps are allowed for the exoskeleton. For the future work, fall prevention assist method for coronal plane should be developed as well.

Acknowledgement

This paper is dedicated to Prof. Toshio Fukuda's 72nd birthday.

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Received November 9, 2020