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Pushing an Object Considering the Hand Reflect Forces by Humanoid Robot in Dynamic Walking

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***Abstract*— This paper discusses pushing a heavy object by a humanoid robot. We modify the whole body motion considering the hand reflecting forces for the walking pattern of a humanoid robot. By assuming that linear and angular momentum of a humanoid robot are calculated, we define the projection of the Center of the Mass(CoM) as ”Dynamically Complemental Zero Moment Point(DCZMP)”, when external forces act to the end-effectors. We propose a new method using the DCZMP for the modification control of CoM position with balancing control. The robot can keep the dynamical balance considering the DCZMP and the walking velocity in both single and double support phase. In addition, for controlling pushing force, we implement an impedance controller with the manipulation and walking velocity controller. The effectiveness of the proposed method is confirmed by simulations and experiments.**

***Index Terms*— Pushing, Humanoid robot, DCZMP, Impedance control.**

Fig. 1. Examples of pushing task.

I. Introduction

Humanoid robots are expected to do some tasks together with or instead of human assistants. If humanoid robots carry out dexterous manipulation as human does, they are used in many places where human lives. Such human being's dexterous manipulation has been studied in some laboratories[1], [2], [3], [4]. These studies focus on the manipulation skill of the industrial manipulator. In recent years, some dynamic simulators has been developed, and the generated patterns for robots are verified correctly and easily on the simulator[5], [6], [7]. There are some studies of control method about whole body balancing and arm/leg coordination, considering the stability for humanoid robots using dynamic simulator[8], [9], [10].They focus on the balancing control for humanoid robots. We also focus on manipulation tasks for humanoid robots and suggested some control schemes of whole body control[11], [12]. We consider the dexterous manipulations is an important factor for the humanoid robots, since it will be used in human life space such as offices, home, construction industry, transportation industry, etc.

Human works mainly using their arms, and their whole body pose is made for dexterous manipulations. By the same token, we consider humanoid robots should decide body position/posture and leg/arm motions following manipulation tasks. We propose this integrated motion control method as ”Mobile Manipulation” control. It determines the foothold which provides a good working condition keeping high ability of the arms to perform tasks and stability considering the ZMP for humanoid robots. This control scheme focuses not locomotion but a manipulation for which the whole body is controlled. In addition, We proposed a new control method for humanoid robots to push a heavy object[13]. By assuming the static balance of the robot's weight and a reflect force acted at the manipulator tip, we define the Complemental Zero Moment Point (CZMP). The Center of Mass(CoM) position is modified to follow the CZMP which moves according to the change of pushing force in both hands. By using these methods, humanoid robot can push an object with the static walking. Such pushing tasks are studied in some laboratories. Harada proposed the real-time walking pattern generation for which a humanoid robot pushes a heavy object by hands[14]. Hwang proposed a method to push wall using an impulse[7]. These pushing techniques are realized in the double supported phase which humanoid robot stands on both feet. However, there is no research on a humanoid robot pushing an object according to the dynamic walking pattern.

In this paper, we deal with a pushing task by a humanoid robot and a balancing control when the external force acts to the end-effectors with dynamic walking. We analytically consider obtaining the CoM modification for ZMP trajectory given by dynamic walking pattern. We newly define Dynamically Complemental Zero Moment

Point(DCZMP) considering the force on both hands and the CoM acceleration.

First, we discuss CoM positional modification control considering reflect force on both hands and acceleration of the CoM for humanoid robots in Section 2. In Section 3, we explain the whole body control scheme using resolved momentum control and implement the DCZMP to the calculation of the reference momentum. Section 4 explains a method combining a walking pattern and a modification CoM control for manipulating pushing forces. Dynamic simulations and experiments on real robot HRP-2 show that the proposed methods can carry out the pushing task with a dynamic walking in Section 5.

II. CoM POSITION CONTROL CONSIDERING HAND REFLECT FORCES AND CoM ACCELERATION

In our previous paper, we proposed a method modifying CoM position to follow Compliment Zero Moment Point(CZMP) which is defined considering reflect force on both hands by assuming static balance for pushing tasks[13]. In this paper, we define Dynamic Compliment Zero Moment Point considering dynamical accelerations as for the dynamical balance on a pushing task with walking.

In this section, we assume the generalized model of humanoid robot as a linear pendulum model which has a velocity $\dot{\mathbf{X}}_C$, an acceleration $\ddot{\mathbf{X}}_C$ and a reflect forceF_E at the hand frame(**Fig.2**). Σ_F, Σ_E and Σ_C are each represented to the frame of a certain point inside the support polygon, the end-effector and the CoM. Let the force and torque on the hand and foot frame and the mass of the robot be $\mathbf{F}_E$,$\mathbf{F}_F$, τ_E, τ_F and $\tilde{m}$ respectively. The relational expression of momentum P and angular momentum L at the foot frameΣ_F are calculated as follows:

$$\begin{cases} \mathbf{F}_F + \mathbf{F}_E - \tilde{m}(\mathbf{g} + \ddot{\mathbf{X}}_C) = \dot{\mathbf{P}}_F \\ \tau_F + \tau_E - \hat{\mathbf{r}}_{FC}\tilde{m}(\mathbf{g} - \ddot{\mathbf{X}}_C) - \hat{\mathbf{r}}_{FE}\mathbf{F}_E = \dot{\mathbf{L}}_F \end{cases} \tag{1}$$

where, P_F and L_F denote whole body momentum and angular momentum at the foot frameΣ_F. $\hat{}$ is an operator as cross product. Here, if the momentum and the angular momentum at the frame of CoM are P and L, the relationship of the P_F, L_F, P and L are as follows:

$$\begin{cases} \dot{\mathbf{P}}_F = \dot{\mathbf{P}} \\ \dot{\mathbf{L}}_F = \dot{\mathbf{L}} - \dot{\hat{\mathbf{r}}}_{FC}\mathbf{P} - \hat{\mathbf{r}}_{FC}\dot{\mathbf{P}} \cong \dot{\mathbf{L}} - \hat{\mathbf{r}}_{FC}\dot{\mathbf{P}} \end{cases} \tag{2}$$

From eq.(1) and (2), the ZMP at the foot frame is given by

$$\begin{aligned} ZMP_x &= \tau_{FY}/f_{FZ} \\ &= (\dot{L}_y - r_{FCz}\dot{P}_x - \tau_{Ey} + \tilde{m}(r_{FCx}(g_z - \ddot{X}_{CZ}) \\ &\quad - r_{FCz}\ddot{X}_{CX}) + r_{FEx}F_{Ez} + r_{FEz}F_{Ex})/ \\ &\quad (\dot{P}_z - F_{Ez} + \tilde{m}g_z) \end{aligned} \tag{3}$$

$$\begin{aligned} ZMP_y &= \tau_{FX}/f_{FZ} \\ &= (\dot{L}_x - r_{FCz}\dot{P}_y - \tau_{Ex} + \tilde{m}(r_{FCy}(g_z - \ddot{X}_{CZ}) \\ &\quad - r_{FCz}\ddot{X}_{CX}) + r_{FEy}F_{Ez} + r_{FEz}F_{Ey})/ \\ &\quad (\dot{P}_z - F_{Ez} + \tilde{m}g_z) \end{aligned} \tag{4}$$

where, the subscript x, y, z denote direction on the world frame. These equations show we can manipulate the ZMP of the humanoid robot by controlling the linear and angular momentum $\mathbf{P}$ and $\mathbf{L}$ around the CoM.

For the purpose of the pushing a task object by hands, the vector from the origine of the foot frame to the manipulator tip $\mathbf{r}_{FE}$ is settled by considering manipulability and joint limits. Let us assume the desired ZMP is given as ZMP_{xd} and ZMP_{yd}, the modification vector of CoM($\mathbf{r}_{FC}$) is calculated by using eq.(3) and (4) as follows:

$$\begin{aligned} r_{FCx} &= ((\tilde{m}g_z - F_{Ez} + \dot{P}_z)ZMP_{xd} - \dot{L}_y + r_{FCz}\dot{P}_x \\ &\quad + \tau_{Ey} + \tilde{m}r_{FCz}\ddot{X}_{Cx} - r_{FEx}F_{Ez} - r_{FEz}F_{Ex}) \\ &\quad /(\tilde{m}(g_z - \ddot{X}_{Cz})) \end{aligned} \tag{5}$$

$$\begin{aligned} r_{FCy} &= ((\tilde{m}g_z - F_{Ez} + \dot{P}_z)ZMP_{yd} + \dot{L}_x + r_{FCz}\dot{P}_y \\ &\quad - \tau_{Ex} + \tilde{m}r_{FCz}\ddot{X}_{Cy} - r_{FEy}F_{Ez} - r_{FEz}F_{Ey}) \\ &\quad /(\tilde{m}(g_z - \ddot{X}_{Cz})) \end{aligned} \tag{6}$$

These equations show the projection of CoM position$\mathbf{r}_{FC}$ becomes different from the real ZMP by the reaction force applied at the hands and CoM accelerations. We define the CoM position as "Dynamically Complemental ZMP"(DCZMP).

By assuming the static balance, the Complemental ZMP moves linear according to the measured forces at the manipulator tip positions. If the humanoid robot acted a large force to the task object with its manipulator tips, the CoM position of the robot closed to manipulator tip position. Additionally, by assuming the model has accelerations, the CoM position should be moved to the accelerated direction.

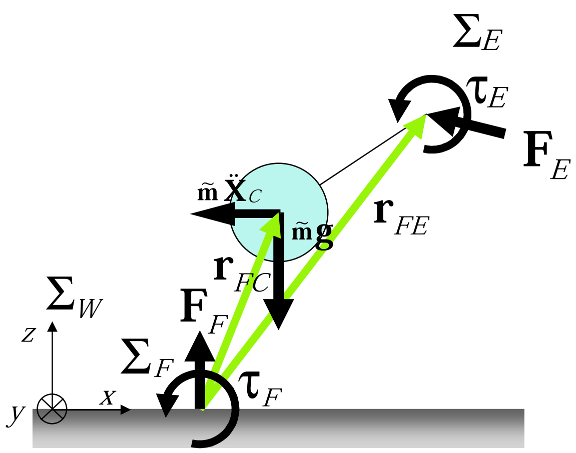

Fig. 2. Simple model with external force to the manipulator.

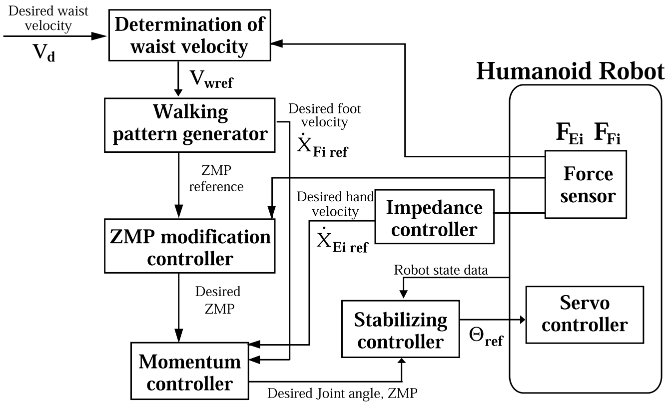

Fig. 3. Control flow.

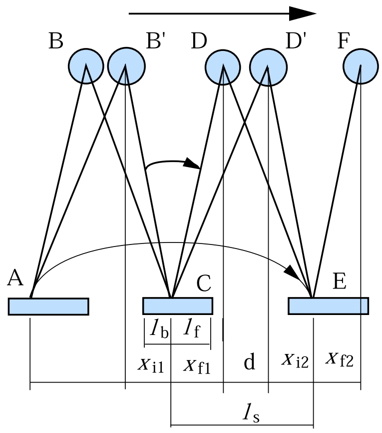

Fig. 4. Walking pattern and foot size.

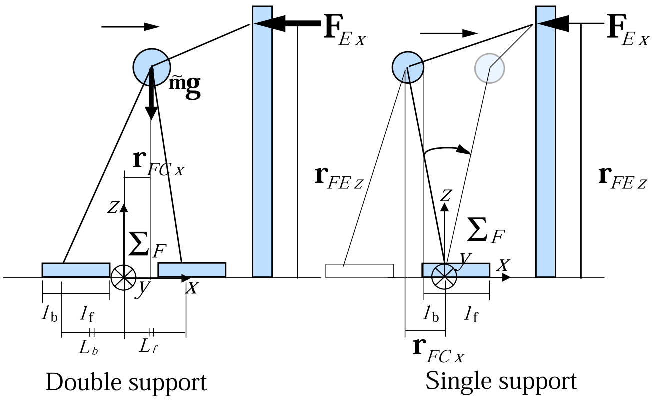

Fig. 5. Double and single support phase.

III. Whole Body Motion Generation

To control a humanoid robot that is the same size as a human body for various tasks of manipulation and the whole body motions, we should control each joint considering each body parameter. Using the robot parameters, we can control each joint considering the whole body momentum and angular momentum by the resolved momentum control scheme[15]. For the pushing tasks using both hands, we control the foot and hand positions manipulating the ZMP. The control equations are calculated in our previous paper[13].

We define the required momentum $\mathbf{P}_{ref}$ and $\mathbf{L}_{ref}$ as follows:

$$\begin{cases} \mathbf{P}_{ref} & = & \tilde{m}\dot{\mathbf{C}}_{ref} + \tilde{m}\mathbf{K}_P(\mathbf{r}_{FC} - \mathbf{C}) \\ \mathbf{L}_{ref} & = & \mathbf{0}_{3\times 1} \end{cases} \tag{7}$$

where, $\mathbf{C}_{ref}$, $\mathbf{C}$ and $\mathbf{K}_P$ denote the desired CoM position, the current CoM position and the coefficient matrix which has a fixed positive number. We can control the position of CoM by manipulating the linear momentum $\mathbf{P_{ref}}$ using eq.(5) and (6). The first term of this equation is linear momentum calculated from target velocity of the CoM, the second term is modification control using a difference between the current position and desired trajectory. Additionally, we assume the angular momentum is zero.

IV. Pushing strategy with walking pattern

We assume a linear inverted pendulum model as a walking pattern of a humanoid robot[16]. The walking pattern is calculated by "Preview Control of Zero-Moment Point"[17]. Whole-body joint angles, that satisfy desired feet, CoM and ZMP trajectory, are culculated by resolved momentum control. The robot modifies its own CoM position to the DCZMP shown in the former session. By the modification, it is possible to keep hand reflect forces from the pushing task. **Fig. 3** shows the control flow.

First, we command a desired walking velocity to the walking pattern generator. When the length of stride becomes steady, the generated pattern can be discribed as **Fig.4** in the sagittal plane. l_s denotes the generated step length. We define the stable foot size from the landing point as the heel is l_b and the tiptoe is l_f(**Fig.5**).

We consider the motion in double support state. By assuming the hand reflect forces have values only in the x direction, $\dot{L}_y = 0$, $\tau_{Ey} = 0$, $\ddot{X}_{Cz} = 0$ and $F_{Ez} = 0$, the $\mathbf{F}_{Ex}$ is calculated as follows:

$$F_{Ex} = \tilde{m}gZMP_x + r_{RCz}\dot{P}_x - \tilde{m}(r_{FCx}g - r_{FCz}\ddot{X}_{CX})/r_{FEz} \tag{8}$$

When the ZMP is located at the heel of the rear foot, the maximum force F_{dmax} in the double support phase is calculated by

$$F_{dmax} = \tilde{m}g(\mathbf{r}_{FCx} + L_b + l_b)/\mathbf{r}_{FEz}. \tag{9}$$

If the $\mathbf{F}_{Ex}$ has small value rather than the F_{dmax}, the pushing motion can be continued.

When the robot is supported by a single leg, the robot is weak in the reflect force from the forward direction and it is difficult to generate the pushing force until the CoM position is over the support position in the x direction. Thus, we give zero reference to the velocity of the manipulator tip in the world frame and implement impedance control to move flexibly against unexpected force. After the CoM position passes the heel position, the pushing force and the muximum force in the x direction is calculated by the same

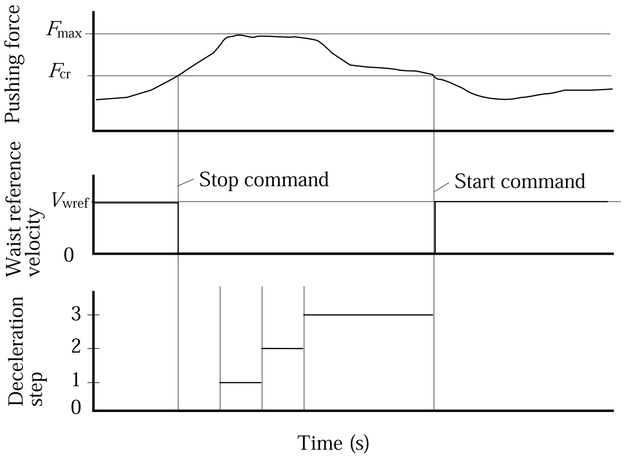

Fig. 6. Pushing force and deceleration walking step.

equation in the double support phase.

Here, we consider the case of acting impulse force at the hands. The walking pattern cannot stop immediately. Considering the command of the walking pattern, the robot can stop within three steps. Hence, we should consider the worst case of three steps in **Fig.6**. When the robot pushes the object by the hands, the body of the robot cannot move to the front of the hand position. As a matter fact, the robot should be stopped before the body is over the manipulator tip position. We define the limit of the reference velocity based on the length from the body to the manipulator tip. The limit step length becomes $3l_s$. The length from the body to the manipulator tip D_{BE} has to satisfy following equation.

$$3l_s < D_{BE} \tag{10}$$

The conditions to give stop command are based on the expected pushing force F_{cri} which is calculated by the relation between rear leg L_b and the CoM position as follows:

$$F_{cri} = \tilde{m}gL_b/\mathbf{r}_{FEz} \tag{11}$$

In the case of F_{Ex} becomes larger than F_{cri}, the reference velocity of walking is set zero. We implement impedance control to the manipulator for controlling the pushing force until the robot starts to walk. The impedance control equation is as follow:

$$F_{Ex} = M_i\ddot{X} + B_i\dot{X} + K_i(X - X_{i0}) + F_{cri} \tag{12}$$

where, M_i, B_i and K_i denote virtual mass, friction and spring coefficient. $\ddot{X}$, $\dot{X}$ and X denote acceleration, velocity and position of the manipulator tip in the world frame. X_{i0} denotes the hand position of the moment the F_{Ex} becomes larger than the F_{cri} in the world frame. By assuming the stable of the balance is compensated by the heel, the virtual spring coefficient is calculated as follow:

$$F_{err} = \tilde{m}gl_b/rFEz = K_i l_b \tag{13}$$

where F_{err} denotes the compensating force by the heel. When the length from the body to the manipulator tip position is larger than D_{BE}, and F_{Ex} has lower value than F_{cri}, the walking velocity is set and the robot starts to walk again.

By using the above controller, it enables a humanoid robot to carry out pushing operation making the CoM position trajectory assumed that reflect force does not act a hand to follow the DCZMP in both single and double support phases.

V. Experiments

A. Simulation on OpenHRP

First, we simulate a proposed method on OpenHRP[6], [5]. We prepare two task objects which one of the weight is 5.0 kg and anonther is 12kg. We define the static and dynamic coefficient of friction between the floor and these task objects are set 0.6 and 0.5 respectively.

The walking pattern generator makes gate motion by the command of the desired weighst velocity. We set the cycle of the walking T as 0.8 sec. which consists of the single support phase 0.7 sec. and double support phase 0.1 sec. In the case we give 0.05 m/s for the desired walking velocity, the step length l_s, d, x_i and x_f are generated about 0.04m, 0.005m, 0.0175m and 0.0175m.

In this simulation, we assume the foot area whose heel l_b and toe l_f positions are set 0.05m and 0.1m respectively. When the robot pushes the object in forward, the DCZMP should be limited in the foot area so that the robot does not fall down, even if the task object moves faster than the walking velocity or the external forces act to the manipulator tips. In the worst stable phase which is the CoM position located back than the support leg in the x direction at the second starting single support phase, the length from the CoM position to the heel in the x direction is calculated as $l_b - x_i$=0.035m so that the robot can apply the force F_{EX} calculated by eq.(8). By assuming that the modification of the CoM position in x direction takes maximum length 0.1m, the CoM starting position of the single support phase is located in front of the supporting leg so that the pushing force can be acted in the all phases. By assuming the manipulator tip position r_{FEz} is 0.79m, the maximum force is calculated as $F_{Exmax} = 58 \times 9.8 \times (0.1/0.79) = 71.95N$.

First, the robot moves the manipulator tip forward to touch the task object. Next, the robot set the reference walking velocity. **Fig.7** shows snapshots in which humanoid robot pushes the object with walking. **Fig.8** and **Fig.9** show the pushing force and DCZMP reference in x-direction. The pushing force sensed at the manipulator tip is vibration but the humanoid robot can push without falling down in both cases. We can confirm DCZMP becomes larger as the pushing force increases and the required pushing force is generated, if the weight of task object

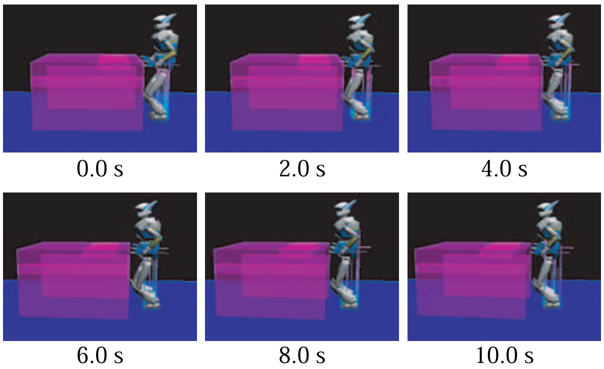

Fig. 7. Simulation result using DCZMP (Object weight:12kg).

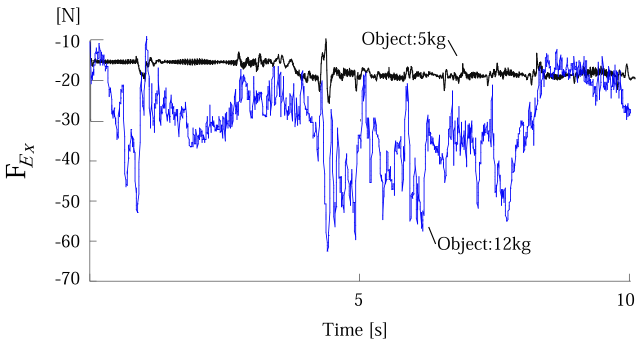

Fig. 8. Pushing force in x direction in simulation.

changes. When the DCZMP is not used for the pushing task, the humanoid robot falles down like **Fig.10**.

B. *Experiment on HRP-2*

We implement the proposed method to a real humanoid robot HRP-2. We prepared a task object which is consisted of a corrugated paper box fixed on the table of 3kg and the table of 12kg. The table has 4-wheels with brake and we can changes the required pushing force by changing the braked wheel number. If the 4-wheels is not braked, the object is moved by 20-30N force in horizontal direction. If the 4-wheels is braked, the object is moved by 50-60N force, which is lower than F_{Exmax}. As a matter of fact, the robot can push this object.

Fig.11, **Fig.12** and **Fig.13** show snapshots, pushing force and DCZMP trajectory in X_F direction. In the experiment, We can see that the same motion of the simulation is generated to enlarge the pushing force by modifying the CoM position in both cases. The pushing force is changed according to the required pushing force.

Next, we experiment the task that the required force is changed by human who pushes against from the wakling direction for confirming that humanoid robot pushes even if the required power is changed on the way. **Fig.14** and **Fig.15** show snapshots and pushing force. We can see the pushing force F_{Ex} becomes larger than F_{Exmax} and walking reference velocity is set zero by the controller. Humanoid robot not falles down and start to walk again,

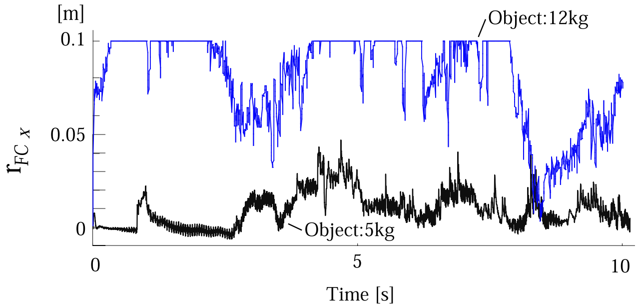

Fig. 9. Modification of the CoM position in simulation.

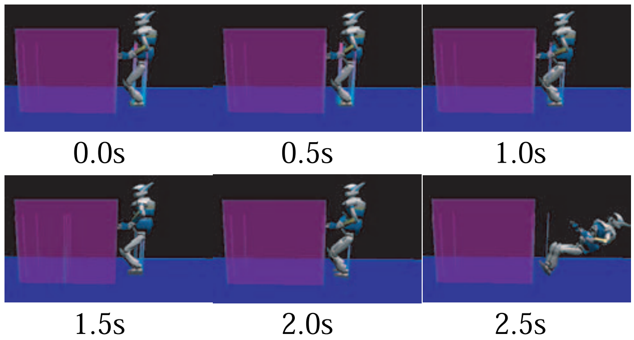

Fig. 10. Simulation result using nomal ZMP (Object weight:5kg).

when the human release the pushing force. The robustness of proposed method is confirmed.

VI. Conclusions

In this paper, we proposed a new pushing control method which calculates the CoM modified position considering the force acted at the both hands and a walking pattern. To manipulate the pushing force, the both arms are controlled by impedance control whose gains are defined by the relationship between the foot step and manipulator tip position. These controller achieves pushing tasks even if the task object is changed or the travel is disturbed. The effectiveness of the proposed method is confirmed by simulation and experimental results.

In future work, we consider the real-time gait planning which is changed to follow the manipulated forces for the robust pushing and controlling the pushing velocity.

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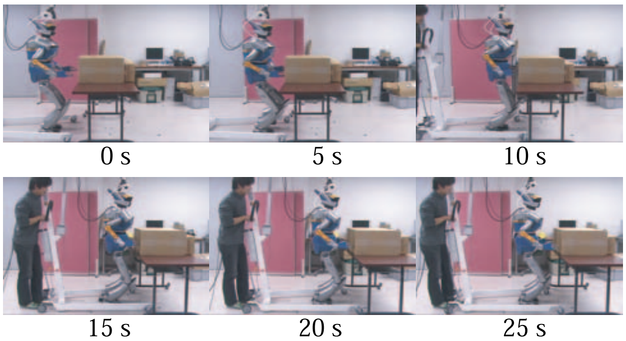

Fig. 11. Experimental result (4-wheels braked).

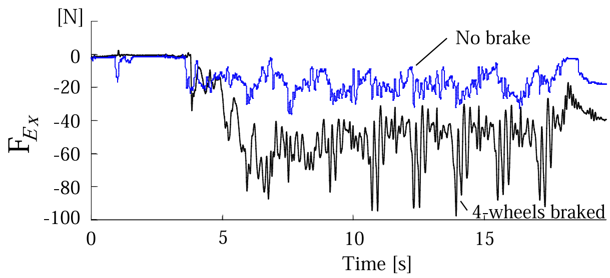

Fig. 12. Pushing force in x direction in experiment.

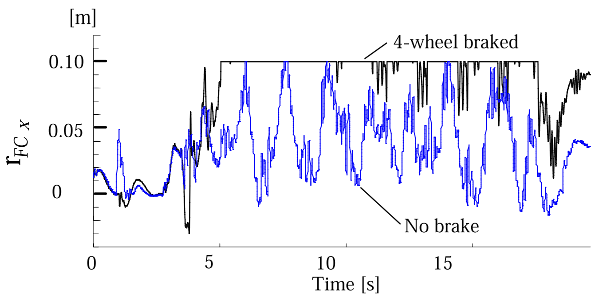

Fig. 13. Modification of the CoM position in experiment.

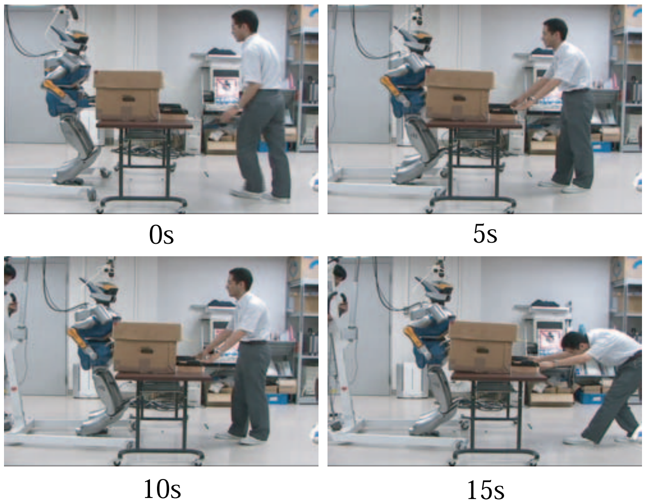

Fig. 14. Modification of the CoM position.

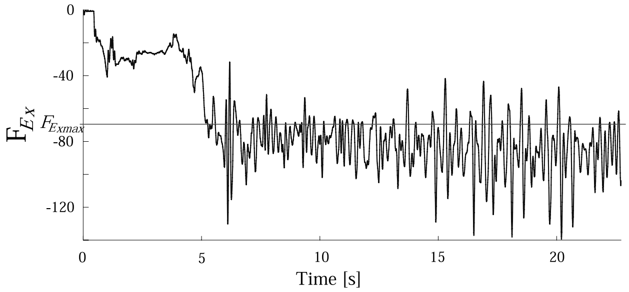

Fig. 15. Modification of the CoM position.

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