

Paper:

Swizzle Movement for Biped Walking Robot Having Passive Wheels

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Biped walking is easily adapted to rough terrain such as stairs and stony paths, but speed and energy efficiency on flat surfaces is less effective than wheeled locomotion. We propose new control for swizzling by biped walking robots using inline skates. Swizzling uses friction force generated by regular passive wheel movement. Our proposal is based on the reaction force on the foot, and new reference position is changed based on reaction force not to be large internal force. Through hardware experiments, the effectiveness of the proposed method was confirmed.

Keywords: biped walking, sliding motion, passive wheeled locomotion, inline skating, swizzle movement

1. Introduction

The advantages of legged over wheel-driven locomotion are clear on rough terrain, especially in biped walking easily adapted to discrete surfaces such as spiral stairs, ladders, and stony paths. The opposite is true on flat terrain, however, where wheeled locomotion outperforms legged locomotion in speed and energy efficiency.

Alternatives have been studied that switch between legged walking and wheeled locomotion based on terrain [1, 2]. The self-contained leg-wheeled bipeds developed by Matsumoto et al., for example, transverse stairs in biped walking mode [2], but stability problems make it difficult for them to walk on rough terrain and to deal with stairs, because their feet are wheels. We developed an active driven foot, Waseda Shoes - No.2 (WS-2) [3], switching between biped and wheeled movement depending on the terrain. A biped with this foot can move rapidly over a flat plane in wheeled locomotion. These hybrid vehi-

cles' active wheels, however, tend to be extremely heavy and bulky, whereas such feet should be light in weight and uninfluenced by the inertia of moving parts.

We propose leg-wheel hybrids using passive wheels. The roller-walker [4] developed by Endo and Hirose switches between four-legged walking and passive wheeled locomotion, but their proposal is difficult to apply to biped robots.

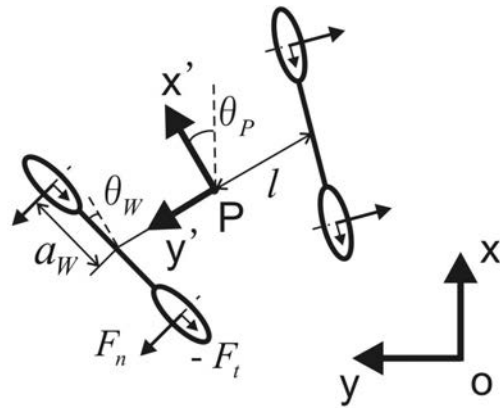
Previous research on switching biped walking and wheeled locomotion using passive wheels can be classified into two types of sliding:

- Swizzling using friction generated by regular passive wheel movement [5–7]
- Skating using kinetic energy generated by kicking [8, 9]

In this research, we focused on swizzling. Kumagai [5] and Utsumi [6] used special roller-skate feet that change the turning curvature by inclining the foot about a roll axis. On the other hand, although the BSR-1 developed by Higano et al. [7] uses normal inline skates, the foot position is controlled by a position control. So, the robot becomes unstable during swizzling due to large internal force.

In this paper, we propose an inline skate system, Waseda Shoes - No. 3 (WS-3), for biped walking robots, together with new control to realize a swizzling, which is a sliding movement using wheel friction by moving skates regularly. Applying position control, we measure step force when changing from static to dynamic friction. It means the robot becomes unstable. We devised new control to change foot reference position based on the foot reaction force.





- Σ_o : Fixed coordinate system
- Σ_p : Moving coordinate system
- a_w : Length between the wheel and the center of the foot
- θ_w : Angle between x' axis and each foot
- θ_p : Angle between x and x' axis
- l : Length between P and the center of the foot
- F_t : Sagittal force acting on wheel
- F_n : Lateral force acting on wheel

Fig. 1. Position and direction of wheels.

2. Sliding by Inline Skates

2.1. Swizzling Principle

Swizzling develops thrust using drag anisotropy in which the coefficient of wheel rolling friction is small and the coefficient of wheel vertical friction is large. Control inputs are the distance between the left and right foot and angles between the x' axis and each foot (Fig. 1).

We start by considering the force acting on one wheel. Relative coordinate $P - x'y'$ is fixed to the robot, and wheel position and direction variables are set as x'_w, y'_w , and θ_w .

$$\begin{aligned} x'_w &= a_w \cos \theta_w \\ y'_w &= l + a_w \sin \theta_w \end{aligned} \quad \dots \dots \dots (1)$$

Wheel position in absolute coordinates is calculated by multiplying a homogeneous transform as follows:

$$\begin{aligned} {}^O\mathbf{P}_P &\equiv \begin{bmatrix} x_w \\ y_w \\ 1 \end{bmatrix} = {}^O_P\mathbf{T}^P\mathbf{P}_W \\ &= \begin{bmatrix} \cos \theta_p & -\sin \theta_p & x_p \\ \sin \theta_p & \cos \theta_p & y_p \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x'_w \\ y'_w \\ 1 \end{bmatrix} \\ &= \begin{bmatrix} a_w \cos(\theta_p + \theta_w) + x_p - l \sin \theta_p \\ a_w \sin(\theta_p + \theta_w) + y_p + l \cos \theta_p \\ 1 \end{bmatrix} \dots \dots (2) \end{aligned}$$

Wheel velocity along the x and y axes, v_x and v_y , is calculated by differentiating Eq. (2) over time. The wheel's sagittal velocity v_t and lateral velocity v_n are obtained by multiplying Eq. (2) by a rotation matrix.

$$\begin{bmatrix} v_t \\ v_n \end{bmatrix} = \mathbf{R}_Z(-\theta_p - \theta_w) \begin{bmatrix} v_x \\ v_y \end{bmatrix} \dots \dots \dots (3)$$

$$\mathbf{R}_Z(\theta) \equiv \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix}$$

If dynamic friction is generated, force acting on a wheel is calculated using the above equation as follows, disregarding viscous wheel friction assuming that it is negligible:

$$\begin{aligned} F_t &= -\mu_t N_w \text{sign} v_t \\ F_n &= -\mu_n N_w \text{sign} v_n \end{aligned} \quad \dots \dots \dots (4)$$

where N_w is normal force acting on a wheel from the ground. μ_t is the coefficient of wheel rolling friction. μ_n is the coefficient of wheel vertical friction.

The x' -component of Eq. (4) is driving force, calculated by multiplying the rotation matrix. The coefficient of wheel rolling friction μ_t is disregarded for simplicity, assuming it is negligible.

$$\begin{aligned} \begin{bmatrix} F_{x'} \\ F_{y'} \end{bmatrix} &= \mathbf{R}_Z(-\theta_w) \begin{bmatrix} F_t \\ F_n \end{bmatrix} \\ &= -\mu_n N_w \text{sign} v_n \begin{bmatrix} \sin \theta_w \\ \cos \theta_w \end{bmatrix} \dots \dots (5) \end{aligned}$$

Movement here is limited to back and forth, with left and right legs moving symmetrical to the x' axis. Assuming that normal force acting on each wheel from the ground is the same, lateral reaction force $F_{y'}$ is canceled and only sagittal reaction $F_{x'}$ remains in driving.

2.2. Control Based on Foot Reaction Force

In this research, the control objects are foot position and force that acts on feet. Force control is supplementary, and the essential importance is foot position determining support condition of a robot, i.e., actual foot position should follow a predetermined trajectory to develop constant thrust and should not deviate from its reference trajectory.

Compliance control [10] or virtual internal model following control [11] may be used to limit large internal force. In such control, the actual position of a robot's end effector deviates from its reference position based on force caused by mechanical interaction between the robot and its working environment. Hybrid control [12] that deals with position and force evenly is not suitable to our purpose, however, which is to limit force to a certain value, not to match force to the reference value. In position control, step force is measured when changing from static to dynamic friction and a robot becomes unstable due to the high control input.

We devised new control to change foot reference position in the time domain based on foot reaction force. This control has two purposes – to limit internal force and to prevent high increments of foot reference position if foot reaction force is too big. To do so, our control consists of two key points. First, reference foot position is set by transforming a basic pattern function in the time domain to limit foot position to a certain trajectory. Second, the change in reference position is determined using a gain function based on force data obtained by foot force sen-

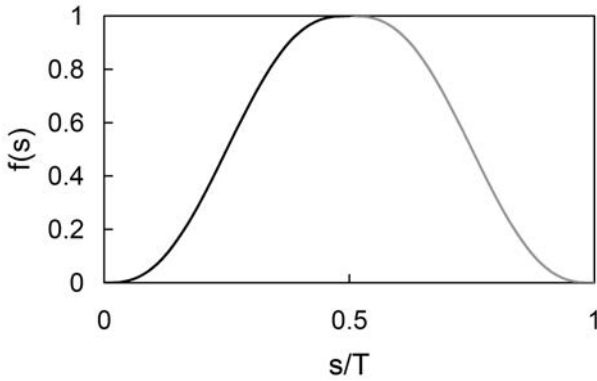


Fig. 2. Basic pattern function $f(s)$.

sors, i.e., reference position is automatically changed to limit large internal force.

These key points are detailed below.

2.2.1. Basic Pattern Function

Basic pattern function $f(s)$ consists of repetition connected two fifth-order functions (Fig. 2).

$$f(s) \equiv \begin{cases} f_{OPEN}(s) & (0 \leq s \leq \frac{T}{2}) \\ f_{CLOSE}(s) & (\frac{T}{2} < s \leq T) \end{cases} \quad \dots \quad (6)$$

$$f_{OPEN,CLOSE}(s) = as^5 + bs^4 + cs^3 + ds^2 + es + f$$

Although periodic functions such as sine waves are substitutable, the fifth-order function has the advantage of enabling the starting velocity to be set to 0. To calculate fifth-order function coefficients, boundary conditions are given as follows:

$$i) 0 \leq s \leq \frac{T}{2}$$

$$\begin{aligned} f(0) = 0, \quad f'(0) = 0, \quad f''(0) = 0, \\ f(\frac{T}{2}) = 1, \quad f'(\frac{T}{2}) = 0, \quad f''(\frac{T}{2}) = 0 \end{aligned} \quad \dots \quad (7)$$

$$ii) \frac{T}{2} < s \leq T$$

$$\begin{aligned} f(\frac{T}{2}) = 1, \quad f'(\frac{T}{2}) = 0, \quad f''(\frac{T}{2}) = 0, \\ f(T) = 0, \quad f'(T) = 0, \quad f''(T) = 0 \end{aligned} \quad \dots \quad (8)$$

Coefficients are obtained, and one period of the basic pattern function with a period of T is expressed as follows:

$$\begin{aligned} f_{OPEN}(s) &= 192 \left(\frac{s}{T}\right)^5 - 240 \left(\frac{s}{T}\right)^4 + 80 \left(\frac{s}{T}\right)^3 \\ f_{CLOSE}(s) &= -192 \left(\frac{s}{T}\right)^5 + 720 \left(\frac{s}{T}\right)^4 - 1040 \left(\frac{s}{T}\right)^3 \\ &\quad + 720 \left(\frac{s}{T}\right)^2 - 240 \frac{s}{T} + 32 \end{aligned} \quad (9)$$

This function is enhanced to make it applicable to all periods, and is defined as position-based pattern function $l_B(s)$:

$$\begin{aligned} f_B(s) &\equiv f\left(s - T \text{int}\left(\frac{s}{T}\right)\right) \\ l_B(s) &\equiv L f_B(s) + L_0 \end{aligned} \quad \dots \quad (10)$$

where $\text{int}(x)$ in the equation is the function to return the integer portion of x . L is the amplitude of foot reference position. L_0 is the initial value of foot reference position.

2.2.2. Gain Function

Reference position is varied based on internal forces in this algorithm, so it is important to decide the function that makes the connection between internal force and the amount foot positioning changes.

Because swizzling uses friction for movement, small internal force should not be limited. When internal forces is small, gain function $g(F) = 1$, and foot position is changed based on the predetermined basic pattern function. Large internal force should be limited not to influence foot position control so that when internal force is large, gain function $g(F) = 0$ and foot position does not change until internal force becomes small. When the gain function changes from 0 to 1, the fifth-order function is used to connect two conditions smoothly. Gain function $g(F)$ is defined as follows:

$$g(F) \equiv \begin{cases} 0 & (F < F_{\min}) \\ g_L(F) & (F_{\min} \leq F \leq F_{\min} + \Delta) \\ 1 & (F_{\min} + \Delta < F < F_{\max} - \Delta) \\ g_H(F) & (F_{\max} - \Delta \leq F \leq F_{\max}) \\ 0 & (F > F_{\max}) \end{cases} \quad (11)$$

$$g_{L,H}(F) = as^5 + bs^4 + cs^3 + ds^2 + es + f$$

where F_{\min} is the minimum internal force. F_{\max} is the maximum internal force. Δ is the interpolation margin of the gain function.

To calculate coefficients of the fifth-order function, boundary conditions are as follows:

$$i) F_{\min} \leq F \leq F_{\min} + \Delta$$

$$\begin{aligned} g_L(F_{\min}) = 0, \quad g'_L(F_{\min}) = 0, \quad g''_L(F_{\min}) = 0, \\ g_L(F_{\min} + \Delta) = 1, \quad g'_L(F_{\min} + \Delta) = 0, \\ g''_L(F_{\min} + \Delta) = 0 \end{aligned} \quad (12)$$

$$ii) F_{\max} - \Delta \leq F \leq F_{\max}$$

$$\begin{aligned} g_H(F_{\max} - \Delta) = 1, \quad g'_H(F_{\max} - \Delta) = 0, \\ g''_H(F_{\max} - \Delta) = 0, \quad g_H(F_{\max}) = 0, \\ g'_H(F_{\max}) = 0, \quad g''_H(F_{\max}) = 0. \end{aligned} \quad (13)$$

Coefficients are obtained and fifth-order functions $g_L(F)$ and $g_H(F)$ are expressed as follows:

$$\begin{aligned} g_L(F) &\equiv \frac{1}{\Delta^5} \sum_{n=0}^5 G_{Ln} F^{5-n} \\ G_{L0} &\equiv 6 \\ G_{L1} &\equiv -15(2F_{\min} + \Delta) \\ G_{L2} &\equiv 10(6F_{\min}^2 + 6F_{\min}\Delta + \Delta^2) \\ G_{L3} &\equiv -30F_{\min}(2F_{\min}^2 + 3F_{\min}\Delta + \Delta^2) \\ G_{L4} &\equiv 30F_{\min}^2(F_{\min}^2 + 2F_{\min}\Delta + \Delta^2) \\ G_{L5} &\equiv -F_{\min}^3(6F_{\min}^2 + 15F_{\min}\Delta + 10\Delta^2) \end{aligned} \quad (14)$$

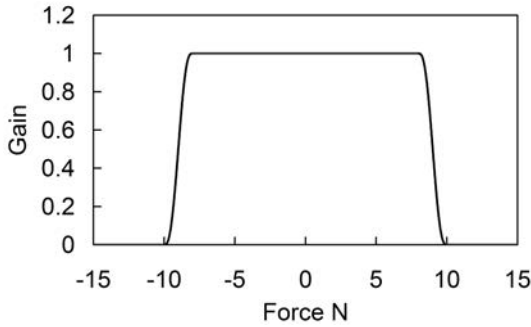


Fig. 3. Gain function $g(F)$.

$$\begin{aligned}
 g_H(F) &\equiv \frac{1}{\Delta^5} \sum_{n=0}^5 G_{Hn} F^{5-n} \\
 G_{H0} &\equiv -6 \\
 G_{H1} &\equiv 15(2F_{\max} - \Delta) \\
 G_{H2} &\equiv -10(6F_{\max}^2 - 6F_{\min}\Delta + \Delta^2) \\
 G_{H3} &\equiv 30F_{\max}(2F_{\max}^2 - 3F_{\max}\Delta + \Delta^2) \\
 G_{H4} &\equiv -30F_{\max}^2(F_{\max}^2 - 2F_{\max}\Delta + \Delta^2) \\
 G_{H5} &\equiv F_{\max}^3(6F_{\max}^2 - 15F_{\max}\Delta + 10\Delta^2).
 \end{aligned} \tag{15}$$

Figure 3 is an example of the gain function when $F_{\min} = -10$ N, $F_{\max} = 10$ N and $\Delta = 2$ N.

2.2.3. Calculation of Foot Reference Position

The foot trajectory is limited by the basic pattern function, and a temporary increment is determined by the gain function.

Parameter s corresponding to present reference position is calculated using the inverse function of position-based pattern function $l_B(s)$.

$$s_i = l_B^{-1}(l_i) \dots \dots \dots (16)$$

Because position-based pattern function $l_B(s)$ is a periodic function and partially a fifth-order function, it is not possible to derive the inverse function analytically, so the solution is numerically obtained by the Newton-Raphson method based on foot opening or closing.

After parameter s corresponding to the present reference position is determined, variation Δl is calculated by multiplying the differential value of the basic pattern function by gain. Gain ranges only from 0 to 1, so even if large force is input, reference position does not exceed the maximum value of basic pattern function.

$$\Delta l(F, l_i) = g(F) \frac{dl}{dt}(s_i) \dots \dots \dots (17)$$

The next reference position is calculated by the present reference position and reaction force as follows:

$$l_{i+1} = \Delta l(F, l_i) + l_i. \dots \dots \dots (18)$$

2.2.4. Calculation of Foot Reference Angle

Reference angles of the left and right feet are determined by shifting by a predetermined phase based on foot

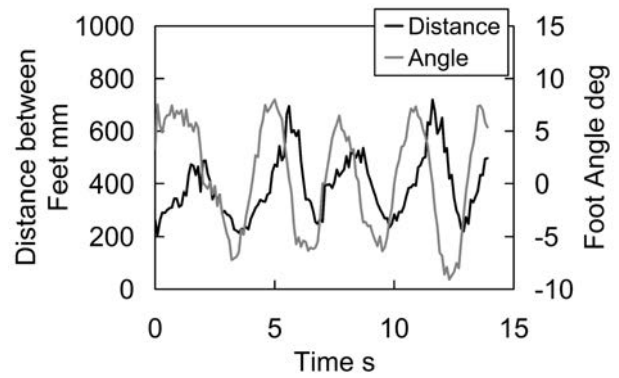


Fig. 4. Swizzle motion of a human.

reference position. To realize swizzling, the phase difference between the position and angle is important, as detailed later. If the position and angle of the feet are controlled independently, the problem arises that the phase shifts. The direction of robot movement is determined by phase shifting.

$$\begin{aligned}
 s_{i+1} &= l_B^{-1}(l_{i+1}) \\
 \theta_{Li+1} &= \Theta f_B(s_{i+1} - \phi) - \frac{\Theta}{2} \dots \dots (19) \\
 \theta_{Ri+1} &= -\theta_{Li+1}
 \end{aligned}$$

where Θ is the amplitude of foot reference angle θ_W . The foot reference angle is that between the x' axis and each foot (Fig. 1). ϕ is phase shifting between the foot position and foot angle.

2.2.5. Determination of Parameters

Our proposed control has eight parameters, T , F_{\min} , F_{\max} , Δ , L , L_0 , Θ and ϕ .

F_{\min} , F_{\max} , and Δ are determined based on the measurement result of the leg's servo stiffness, which is about 9400 N/m. Experimental results showed that if internal force is less than 70 N, measured position follows reference position well, so these three parameters related to the gain function are set as follows:

$$\begin{aligned}
 F_{\min} &= -70 \sim -100 \text{ N} \\
 F_{\max} &= 70 \sim 100 \text{ N} \\
 \Delta &= \frac{F_{\max}}{2} \text{ N}
 \end{aligned}$$

where Δ is determined empirically.

If the foot angle is 0° when the feet are fully open or closed, thrust is provided constantly. We conducted a basic experiment when phase shifting ϕ is 90° , but the robot stops with the left and right feet parallel to each other because the reference velocity and angular velocity simultaneously become zero. To determine parameters related to the basic pattern function, we analysed swizzling by a human subject based on a video of the swizzling foot with markers (Fig. 4). What is interesting about this figure is that phase shifting between the distance between feet and the foot angle is about 45° . Phase shifting prevents the human subject from stopping at the expense of thrust. Al-

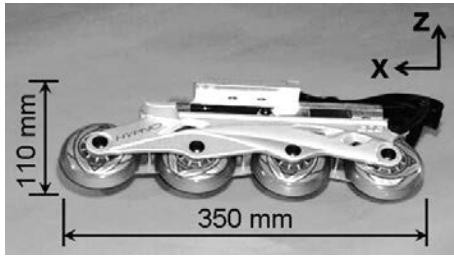


Fig. 5. Inline skate system for biped robots, WS-3.

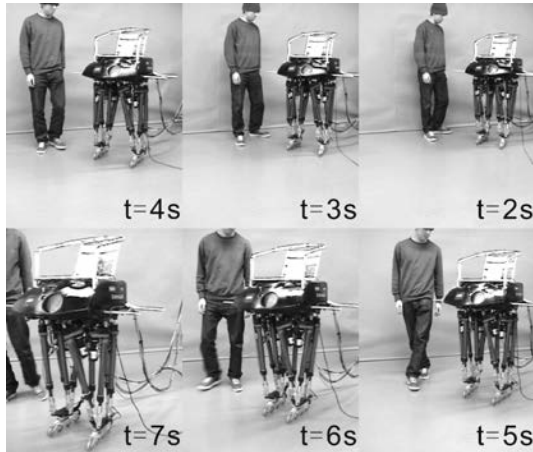


Fig. 6. Skating experiment.

though output characteristics and movable range of actuators differ between human subjects and robots, only the geometric trajectories of the human subject's feet were referred to determine parameters Θ and ϕ . Parameter are determined as follows:

$$\begin{aligned} T &= 1.5 \text{ s} \\ L &= 100 \text{ mm} \\ L_0 &= 115 \text{ mm} \\ \Theta &= 10^\circ \\ \phi &= 45^\circ \end{aligned}$$

where amplitude L and initial value L_0 of foot reference position are determined within the range used in usual biped walking due to the movable range limit. Period T is determined arbitrarily. The smaller the T , the faster the robot moves.

3. Experiments and Discussion

The inline skate system WS-3 we developed (see Fig. 5) is a commercial component attached to the human-carrying biped walking robot Waseda Leg – No. 16 Refined (WL-16R) [13]. Four passive wheels of this skate have low rolling resistance thanks to bearings. They have a large friction coefficient in the perpendicular direction to the rolling direction.

To evaluate our proposed control for swizzling, we measured foot position and internal force. In this experiment, foot position and angle are calculated by solving di-

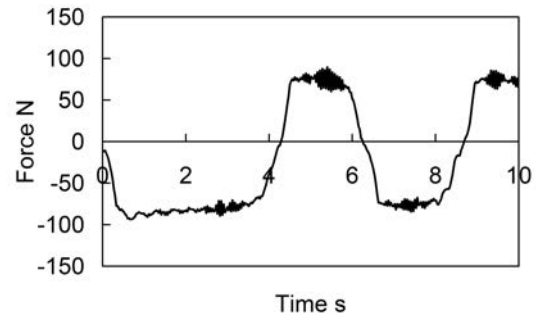


Fig. 7. Left foot reaction force along y axis.

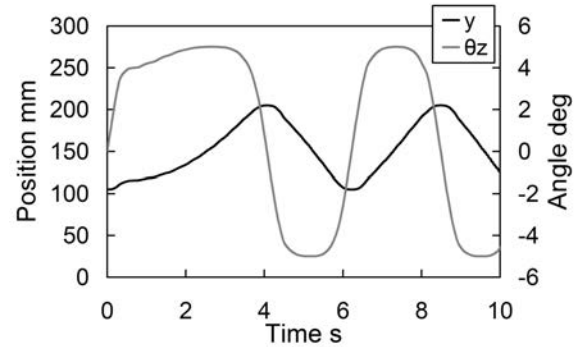


Fig. 8. Left foot response position and angle.

rect kinematics based on individual cylinder length measured by encoders, because the robot does not have a system measuring foot position and angle for the absolute coordinate frame. To measure internal force, we used a 6-axis force torque sensor installed on the foot. We set minimum and maximum internal force F_{\min} and F_{\max} , period T , and phase shifting ϕ between foot position and angle as follows:

$$\begin{aligned} F_{\min} &= -100 \text{ N} \\ F_{\max} &= 100 \text{ N} \\ T &= 1.5 \text{ s} \\ \phi &= 45^\circ. \end{aligned}$$

The sequential photographs of the experiment are shown in Fig. 6. The robot moved about 4 meters during 10 seconds and its travel was measured by a researcher using a rule. Fig. 7 shows force response data along the y axis. Note that internal force is limited within 100 N. Without our proposed control to change reference position based on reaction forces, the robot became unstable during swizzling due to large internal force. Fig. 8 shows left foot response position and the yaw angle, which are changed based on the foot reaction force. Note that smooth swizzling was realized without stopping based on appropriate phase shifting between foot position and angle. Fig. 9 shows the deflection between the left foot reference and the response position and angle. As shown in this figure, servo-following error is very small.

Hardware experiments thus confirmed the effectiveness of our proposal.

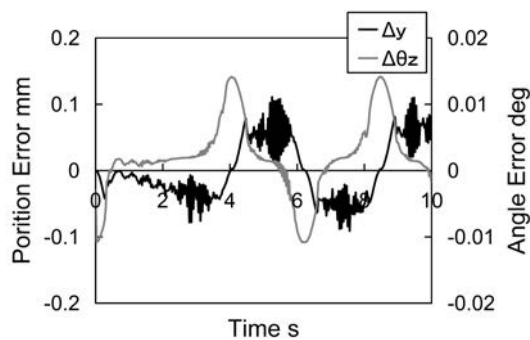


Fig. 9. Deflection of left foot position and angle.

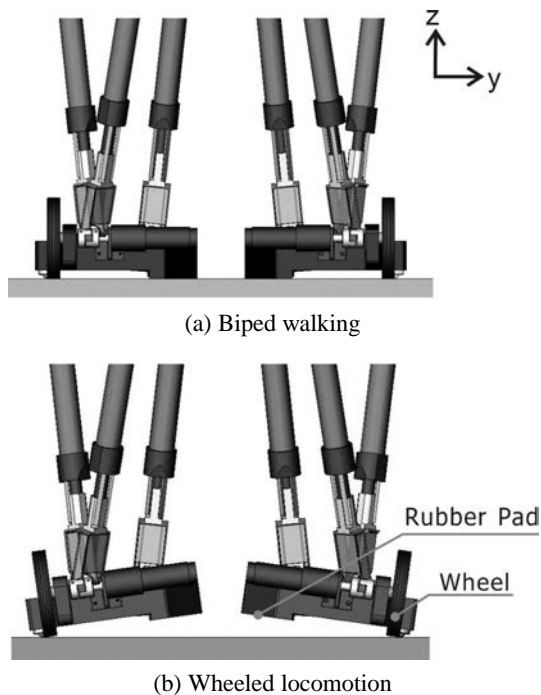


Fig. 10. Switching between biped walking and wheeled locomotion.

4. Conclusions

We developed inline skating, WS-3, for biped walking robots and control to realize swizzling, sliding that uses wheel friction by moving skates regularly. If conventional position control is applied to control the legs movement, large internal force is generated by forcibly moving feet constrained by frictional forces. Our proposal is based on reaction force acting on the feet, and foot reference position is changed based on reaction force not to be large internal force. Hardware experiments demonstrated the smooth swizzling realized and the effectiveness of our proposal.

It is very important in our research to switch between sliding and biped walking. If rubber pads are attached inside the foot and passive wheels outside the foot, modes are switched by tilting both feet outward, as realized in our active driven foot system, WS-2 [3] (Fig. 10). Our next goal is to realize whirling and stopping and to switch between biped walk and wheels depending on the terrain.

Acknowledgements

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Main Works:

- "Unknown Disturbance Compensation Control for a Biped Walking Vehicle," Proc. of the IEEE/RSJ Int. Conf. on Intelligent Robots and Systems, pp. 2204-2209, October 2007.
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- "Quasi-human Biped Walking," Robotica, Vol.24, No.2, pp. 257-268, 2006.
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Main Works:

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Main Works:

- "The Development of the anthropomorphic flutist robot at Waseda University," Int. Journal of Humanoid Robots, Vol.3(2), pp. 127-151, 2006.
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