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Stumbling with optimal phase reset during gait can prevent a humanoid from falling

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Abstract The human biped walking shows phase-dependent transient changes in gait trajectory in response to external brief force perturbations. Such responses, referred to as the stumbling reactions, are usually accompanied with phase reset of the walking rhythm. Our previous studies provided evidence, based on a human gait experiment and analyses of mathematical models of gait in the sagittal plane, that an appropriate amount of phase reset in response to a perturbation depended on the gait phase at the perturbation and could play an important role for preventing the walker from a fall, thus increasing gait stability. In this paper, we provide a further material that supports this evidence by a gait experiment on a biped humanoid. In the experiment, the impulsive force perturbations were applied using push-impacts by a pendulum-like hammer to the back of the robot during gait. The responses of the external perturbations were managed by resetting the gait phase with different delays or advancements. The results showed that appropriate amounts of phase resetting contributed to the avoidance of falling against the perturbation during the three-dimensional robot gait. A parallelism with human gait stumbling reactions was discussed.

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1 Introduction

Human biped gait in its steady state possesses dynamic stability, implying that it may be modeled as a stable limit cycle solution of the neuro–musculo–skeletal system as a coupled nonlinear dynamical system (Taga 1995). Gait responses following single, usually short-lived, force perturbations during steady gait could be viewed as transient dynamics of the underlying system in which the system's state point asymptotes back to the limit cycle. Such responses are often referred to as the stumbling reactions in the field of neurophysiology (Forssberg 1979). The stumbling reactions include lowering and elevating strategies, one of which is chosen by the walking subject depending on the timing, i.e., the phase within the gait cycle at which a type of perturbation is applied (Schillings et al. 1999, 2000; Forner Cordero et al. 2003, 2004), in particular during stumbling over obstacles. The gait cycle duration may change during the reaction, but its steady-state value is reestablished after the transient, leading to the phase reset of the walking rhythm in the Winfree's sense (Winfree 1980; Kawato 1981). For a type of perturbation during human gait, we have demonstrated the amount of the phase reset as the function of the perturbation phase, i.e., phase resetting curve (Kobayashi et al. 2000). Moreover, we showed that the transient duration (settling time) was also phase dependent.

Physiological studies have long been providing evidences in animals and human that the basic walking rhythm is generated by a distributed neural network in the central nervous system (CNS), referred to as the central pattern generator (CPG) (e.g., Grillner 1981; Dimitrijevic et al. 1998), and it has been modeled as an autonomous nonlinear oscillator. Since there is one-to-one correspondence between the CPG oscillations and the walking cycles during steady gait, the phase reset of the walking rhythm during the stumbling reaction is necessarily accompanied with the phase reset of the CPG by the same amount.[1] For a given perturbation, how much should the phase be reset? How long should it take in order to maintain dynamic stability against the perturbations during gait? How are they determined? Although it is intuitively evident that the stumbling reactions with the phase reset provide a basis of maintenance of postural stability during gait, necessary conditions that should be satisfied by the reactions are not trivial. Yamasaki et al. (2003a,b) partly answered the first question by using a mathematical model of biped human walking. Their model was defined on the sagittal plane with seven rigid links, and the ground reaction force was modeled by nonlinear hard springs and viscous elements. They showed, for almost every examined phase of the perturbation, that there exists a range of the optimal amounts of phase reset with appropriate transient durations. Their result was consistent with the experimental result shown by Kobayashi et al. (2000) during human gait. They considered two biped models: one included a mechanism of the optimal phase reset that could prevent the model from a fall in response to a given perturbation (closed-loop model), and the other did not (open-loop, master–slave model) in which the perturbation might lead to falling. Assuming both models span the identical phase space, examination of basin of attraction of each model's limit cycle clarified that the basin of the former model is wider than that of the latter. That is, a state point of the model without phase reset mechanism located outside the basin due to the perturbation could be inside the basin for the model with the appropriate phase reset.

In the present study, we applied the phase resetting mechanism that could increase gait stability to the humanoid gait, and tried to demonstrate experimentally that the stumbling reaction with optimal phase resets can prevent the walking humanoid from a fall. To this end, a humanoid robot was used in this study, and the use of the robot was motivated by the following reasons. (1) Unlike in the case of numerical simulation of biped gait, a real-world robot experiment does not require mathematical modeling of the ground reaction forces and frictions that are usually difficult to deal with. Thus, experimental results can be interpreted without discussing effects of a degree of accuracy of the ground reaction force modeling. (2) The phase resetting mechanism itself merely deals with a modification of gait phase, and thus postural balancing in the mediolateral direction, which has not been taken into account in the sagittal modeling (Yamasaki et al. 2003a,b), is not explicitly considered, but the robot movements occur in the three-dimensional space. The robot experiment here in the real world showed that these issues were not dominant factors for the phase reset mechanism to maintain the gait against perturbations in the anteroposterior direction, and the theory developed for the simple gait model on the sagittal plane could be extended into the real-world gait.

Our experimental approach was straightforward, in which the robot movement in terms of its joint angles just followed a prescribed trajectory and no control mechanisms compensating the perturbation were used other than the phase resetting which involves modification of the prescribed trajectory in response to the perturbation for a certain period of transient time. In this way, we could have a concentrated look at the role played by the phase resetting to increase gait stability. Results confirmed in this study will be discussed with related studies performed during human gait.

2 Methods

2.1 Humanoid robot

A small biped humanoid robot (HOAP-1, Fujitsu, Japan) was used for the study. The height and weight of the robot are 48 cm and 6 kg, respectively. The total degrees of freedom (dof) of the robot are 20, including 6 dof for each leg and 4 dof for each arm. Every dof is actuated by a DC motor controlled locally by a microcomputer. The main control of the robot movement is made by a PC with RT-Linux (FMV-C600, CPU:Pentium4, 1.7 GHz). The microcomputer for each motor receives a desired joint angle every 1 ms from the PC and the high gain local servo mechanism with the microcomputer and the corresponding DC motor forces the joint angle of the robot to coincide with the desired joint angle. Let us denote a sequence of desired joint angles for all of 20 dof used for the current study as the *motion data*. A motion data, represented here in a matrix form just for convenience, included 20 columns corresponding to 20 dof and N rows. A motion data providing a joint angle trajectory of the robot for a time interval N ms from the beginning of the movement to the end was prescribed and fed into the PC controller. The robot includes a three-axial acceleration sensor and a

[1] If we simply assume that the CPG is a master oscillator of the mechanical body-limbs as a slave, the phase reset of the CPG results in that of the walking rhythm. Animal and human gait control systems, however, are not so simple. Nevertheless, such a simplification may help our understanding of gait control.

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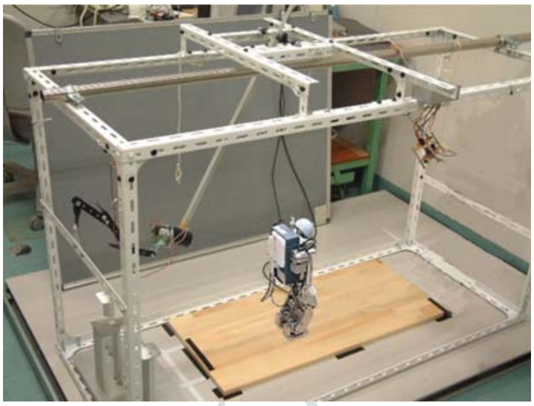
three-axial angular velocity sensor within the body to detect the motion of the center of the body mass. Each of 20 motors has an optical rotary encoder to detect the joint angle. Every joint angle shown below is represented as a relative rotated angle between two adjacent limbs in radian measured from the standard upright standing posture. In cases of the hip and knee, positive joint angles stand for flexion. For the ankle, negative angles for dorsiflexion. Each foot has force sensors at its four corners, and the total ground reaction force (GRF) only in the vertical direction of each foot was obtained as the summation of those, and represented as the ratio to the total weight of the robot (normalized GRF).

2.2 Control gait of the humanoid

In the experiment, basically, only one motion data was used, and all joints of the robot moved in accordance strictly with this motion data, even if the robot was perturbed, unless the motion data provided to the robot was modified. This was possible because of the high gain local servo at every joint. The humanoid gait without any modification from the motion data was used as a reference, and referred to as the *control gait*, and the corresponding motion data as the *control motion data*. Perturbed gaits with some modifications from the control gait will be defined below. The control gait spanned 17,900 ms time interval. The control gait started with a quiet standing posture, and the robot made 12 steps, and then stopped. The middle part of the control gait (about 7,000 ms after the beginning of the gait until about 13,000 ms) could be considered as a steady walking and its gait cycle (period) was about $T \simeq 2,600$ ms. The average walking velocity was 4.3 cm/s. Throughout the study, the robot walking was performed on a pine wooden plate with 2 cm thickness by which the control gait was the most stable (see Fig. 1).

2.3 Perturbation and perturbed gait

Figure 1 shows the experimental setup used for the study. The robot walking was performed on the wooden plate located in the steel-pipe-cage. A hard elastic rubber-hammer with 0.25 kg weight was attached to one edge of an aluminum stick with 62 cm length. The other edge was attached to the top of the cage to behave as a pendulum. The rotational joint of the pendulum was considered as a frictionless hinge. A light steel plate was attached on one face of the hammer, and the pendulum with the hammer was fixed at one end of the cage by an electric magnet, where the pendulum was elevated 30° from the vertical. At the beginning of the robot gait, the electric magnet was powered. During the robot walking,



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the electric power was switched off to release the hammer and then to apply a single impulsive force perturbation to the back of the robot body (trunk). The back of the robot body was covered by a styrol plate with 1 cm thickness to avoid mechanical damages on the robot.

The hammer was released at various timings of the gait so that the perturbation could be applied at various gait phases that covered a whole single gait cycle. Time instants of the hammer impact were set within the interval between 7,600 and 10,300 ms from the beginning of the gait. Those impact timings were separated by 100 ms, and hence, responses of the robot against 28 different impact timings covering the single gait cycle were examined. The magnitude of every perturbation was almost the same, and the peak impact force measured by a digital force gage sensor (FGX-50, Nihon-Densan Sympo, Kyoto) was about 4 N regardless of the horizontal position of the impact. The kinetic energy of the hammer and, of course velocity in the horizontal direction were maximal when the pendulum was at its lowest point, and their values were approximately 0.2 Nm and 1.3 m/s, respectively. In terms of the kinetic energy, the small differences in the magnitude of the perturbation due to the change of position of the robot at the impact varied to less than ±15% of the maximum value. The hammer contact point on the robot's back changed from side to side, since the body trunk swung from side to side with its amplitude about 4 cm with the gait period. Because of this, the hammer contact point

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on the robot's back was slightly left side of the trunk for the first half cycle and right side for the latter half cycle. Moreover, the control gait of the robot always tended to curve slightly leftward due to uncontrollable characteristics of the robot. For these reasons, the impacts during the first and the latter halves of the cycle were not necessarily exactly the same. However, these differences were small with respect to the most important factor: the instants of the hammer's impact with the robot with respect to the gait cycle.

Within the examined impact time interval between 7,600 and 10,300 ms, the gait phase of the robot with the control motion data was as follows. The left foot took off the ground at the time about 7,750 ms, the start of the left swing phase. The time interval from 7,750 to 9,050 ms was the first half cycle of the gait. The early part of this interval until 8,400 s was the right single-stance phase, which could be further divided into the early and late swing of the left leg, and the remaining interval was the double-stance phase. The subsequent time interval from 9,050 to 10,300 ms was the latter half cycle of the gait which started with the left single-stance phase or the early swing phase of the right leg, and then the late swing of the right leg, followed by the double-stance phase.

2.4 Responses of robot to the impact

The impacts made by the hammer acted as the perturbations to the humanoid gait. In response to each impact applied at various phases of the gait, we modified the movement of the robot. An appropriate modification of the robot movement, which we should clarify in this study, might depend on the given perturbation phase. The modification of the robot movement examined here included two parameters. The most important parameter was the amount of phase reset Δn in the unit of milliseconds. That is, in response to the impact, the control motion data was phase shifted. Let us denote the control motion data as $\{x_n\}$ where the subscript n runs from 1 to $N = 17,900$. The phase shift here means that the motion data after the impact was switched from the control motion data $\{x_n\}$ to the *modified motion data* or, equivalently, *phase-shifted motion data* $\{x_{n-\Delta n}\}$. It was phase advanced by an amount of Δn ms, or $(\Delta n/2,600) \times 100\%$ short compared to the control gait cycle, when $\Delta n < 0$ in one case. It was phase delayed, i.e., $(\Delta n/2,600) \times 100\%$ long, when $\Delta n > 0$ in another case. When $\Delta n = 0$, the motion data was not modified, i.e., the same as the control motion data.

The second parameter was the transient duration $\tau > 0$ in the unit of milliseconds. When the motion data was phase shifted from $\{x_n\}$ to $\{x_{n-\Delta n}\}$ at time m ms in response to the perturbation, the desired joint angles at times m and $m + 1$ could change largely for large $|\Delta n|$, leading to a very large joint angular velocity of the robot. Although such a large joint angular velocity required a large amount of motor torque, which could be harmful to the system, our robot system could manage to achieve the corresponding quick movement. In our experiments, however, such a situation was avoided by introducing the transient duration started at the impact and ended at τ ms after the impact. We introduced the transient duration because it could be an influential factor that determines whether or not the perturbed gait could avoid a falling during human and simulated human gait as shown in the previous works (Yamasaki et al. 2003a,b). In order to realize the transient duration, for the impact at time m, we set the modified motion data at time m as x_m, and at time $m + \tau$ as $x_{m-\Delta n+\tau}$. The modified motion data from the time m to $m + \tau$ was determined so that every component of x_m and $x_{m-\Delta n+\tau}$ was connected smoothly using third-order spline functions. Figure 2 illustrates this situation, in which a case with $\Delta n = -800$ ms (the phase was advanced about 30% of the control gait cycle) in response to the impact at 9,500 ms is exemplified. In the figure, hip, knee and ankle joint angles of right leg for the control motion data (dotted curves) and the modified, phase-shifted motion data (solid curves) are superposed. For the first several hundred milliseconds before the impact, waveforms of the control and modified motion were identical. At the impact (the left-most vertical line), they started to separate. In this case, we set the transient duration τ as 200 ms, which corresponds to the interval from the left-most to the second vertical line. Comparing the solid and dotted curves after $\tau = 200$ ms from the impact, it can been seen that the waveforms were the same but the solid modified motion data was phase advanced. See Yamasaki et al. (2003a) for a similar method and a detailed procedure.

In this paper, $\tau = 200$ ms, which corresponded to about 8% of the control gait cycle, was used mostly, except in only two cases where $\tau = 600$ ms corresponding to a long transient was also examined in addition to $\tau = 200$ ms for which the robot was fallen by the impact; but it was highly expected that a longer transient might improve the response of the robot to avoid the fall. Influence of the transient duration on the perturbed robot gait was not be extensively examined in this study, but it has been demonstrated that the transient duration, in addition to the amount of phase reset, was a crucial and phase-dependent determinant of the gait stability against the perturbation during human and simulated human gaits (Yamasaki et al. 2003a,b). See Sect. 4 for related arguments on the transient duration.

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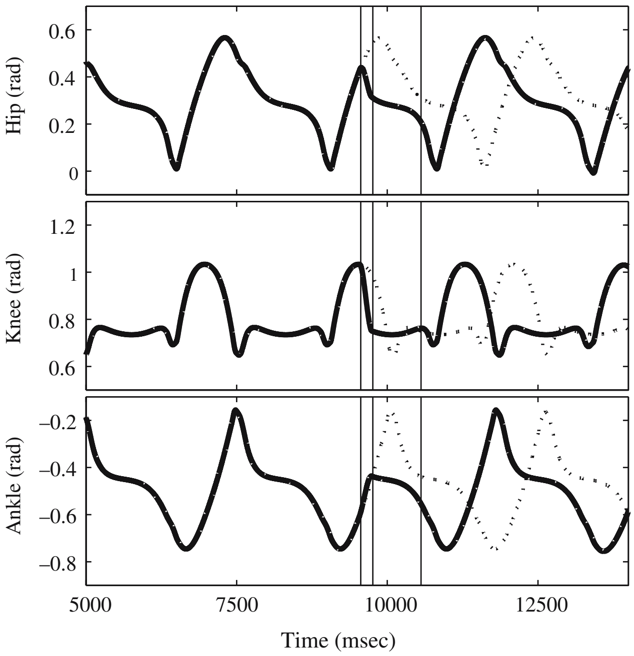

Fig. 2 Procedure of phase resetting in which the motion data was switched from the control to a phase-shifted motion data in response to a detection of the hammer impact. Hip, knee and ankle joint angles of right leg for the control (*dotted curves*) and the phase-shifted motion data (*solid curves*) are superposed. For the first several hundred milliseconds before the impact, waveforms of the control and the phase-shifted motion were the same. At the impact (*left-most vertical line*), they started separation. In this case, the transient duration τ was 200 ms, corresponding to the interval from the *left-most* to the *second vertical line*. Comparing the *solid* and *dotted curves* after $\tau = 200$ ms from the impact, the waveforms are the same but the *solid curves* are phase advanced ($\Delta n = -800$ ms). The time interval from the *second* to the *third vertical line* was 800 ms. See text for details

An appropriate set of the two parameter values, namely, Δn and τ, may provide a way of response for the robot to a given timing of the perturbation so that the robot can continue walking against the hammer impact. If the values of these two parameters are not appropriate, the robot may be fallen by the impact. In this study, we changed these two parameter values, in particular, the value of Δn in a wide range, for each of various timings of the perturbation to look for the optimal values of these parameters.

The impact on the back of the robot was detected by the three-axial acceleration sensor in the body. In particular, we used the acceleration in the front–back direction (α_x). The output value of this sensor varied oscillatorily but with small amplitude during the control gait. When the hammer impacted on the back of the robot, the output value of this sensor markedly and rapidly increased to form a delta function like waveform. The impact time was defined when the sensor output crossed a threshold (14.6 m/s^2). For safety of the experiment, when the robot started falling largely, the local servo mechanism was switched off before the robot completely fell down the ground. This was judged by the output value of the angular velocity sensor (ω_z) with respect to the vertical z axis. More precisely, if an event either $\omega_z < -1.25$ or $\omega_z > 1.13$ rad/s was detected, the local servo was switched off 1,000 ms after the detection, so that the robot stopped the gait motion by letting all joints move freely.

Optimal amounts of phase reset that could avoid falling against the perturbation were systematically explored for various perturbation phases. To complete this, we made 588 impact experiments consisting of different timings of the hammer impact and different amounts of phase reset in response to the impact. For a fixed given amount of the phase reset, the robot performed walking 28 times. For each walking, a perturbation with different impact timing, ranging from 7,600 to 10,300 ms with 100 ms steps, was applied. Such 28 experiments were carried out for 21 different amounts of the phase reset, ranging from −1,000 to 1,000 ms (corresponding to the phase advance and phase delay about 38% of the control gait cycle) including zero phase reset. By those, we obtained 588 pairs of the experimental conditions on the perturbation phase and the amount of the phase reset. When the robot could keep walking despite the perturbation for a given timing and an amount of the reset, the corresponding condition set was considered as "success," otherwise "fail" in which the robot fell down for that timing and reset condition. Note that we determined the intensity of the perturbation (i.e., the initial height of the hammer) so that, even when $\Delta n = 0$ (with no phase reset), the robot did not fall for some intervals of the perturbation phase, which was roughly overlapped with the timing of double support phase of the robot. If the perturbation intensity was higher and the robot could not keep walking without phase reset for any impact timing, the current phase reset mechanism could not work out.

3 Results

Figure 3 exemplifies a response of the robot to the hammer perturbation with the impact at 9,500 ms after the gait onset, which corresponded to the late swing phase of the right leg, when no phase reset was made. All of the joints changed strictly in accordance with the control motion data even after the detection of the hammer impact. In this case, the robot fell down the ground in a second. Note that before the robot fell completely down to the ground, the local servo mechanism

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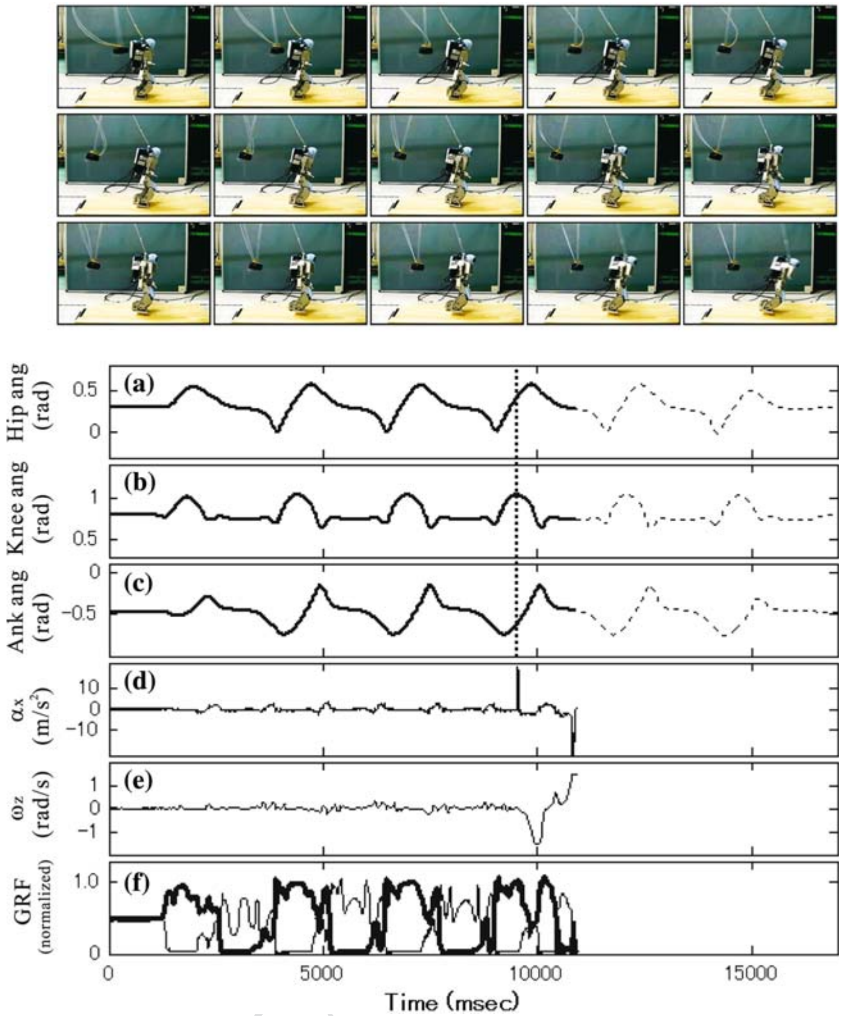

Fig. 3 Response of the humanoid to the impact at $t = 9,500$ ms (the late swing of the right leg) in case without phase reset, leading to a fall. *Top* A sequence of picture frames with 100 ms steps (time evolves from *top-left* just around the impact to *bottom-right*). *Panels a–c* Hip, knee and ankle joint angles of right leg. *Solid curves* are actual robot motions, and *dotted curves* are the control motion data. *d*, *e* The body acceleration in the front–back direction and yaw angular velocity of the body. *f* Ground reaction forces (GRF) of the left (*thick curve*) and the right (*thin curve*) feet. GRF was normalized by the total weight of the robot. The *dotted vertical line* common to *a–c* indicates the instance of the impact detection corresponding to the delta function like change in the body acceleration shown in the *panel d*

of all joints were switched off for safety as mentioned in the method. (See Electronic Supplementary Material Movie 1.)

For the same perturbation with the impact at 9,500 ms at the late swing of the right leg, the phase reset of $\Delta n = -800$ ms (phase advanced about 30% of the control gait cycle) of the motion data in response to the impact detection with the transient duration $\tau = 200$ ms could lead to the maintenance of the gait (Fig. 4). That is, when the control motion data was switched to the corresponding phase-shifted motion data in response to the detection of perturbation, the robot could continue walking without falling after the perturbation. (See Electronic Supplementary Material Movie 2.) In this case, the right leg which was in the late swing at the impact touched the ground quickly after the impact. This response was similar to the lowering strategy that has been identified during human stumbling reaction when the obstacle or the force perturbation at the lower leg from behind was applied at late swing phase (Schillings et al. 2000; Forner Cordero et al. 2003, 2004).

Another example was for the perturbation with the impact at 9,600 ms after the gait onset (late right swing) as shown in Fig. 5. The robot fell down without phase reset for the perturbation with this timing, but the walking could be maintained when the phase reset by amount of 600 ms (phase delay about 20% of the control gait cycle) was employed. (See Electronic Supplementary Material Movies 3 and 4.) In this case, the right leg, which was also in the late swing at the impact, was elevating quickly after the impact, and the swing phase was performed again. The corresponding motion of the robot was similar to the one observed in the human elevating strategy that has been identified during stumbling reaction. Note, however, that the elevating strategy during human gait has been observed when the obstacle perturbation was applied at early swing phase (Schillings et al. 2000; Forner Cordero et al. 2003, 2004), whereas the phase-delayed response with the elevating-like motion shown here was for the perturbation at the late swing phase. See Sect. 4 for this discrepancy. Despite of this discrepancy, the motions of the robot during

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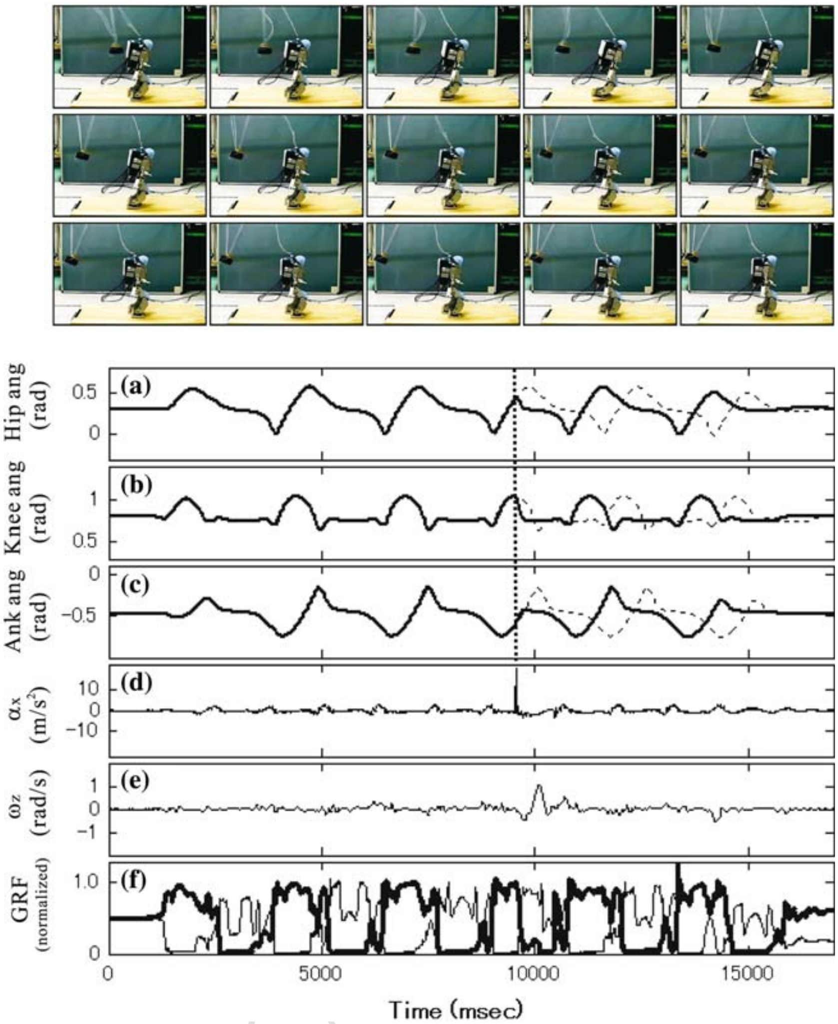
Fig. 4 Response of the humanoid to the impact at $t = 9,500$ ms as in Fig. 3, but with the phase resetting by the amount of -800 ms (phase advanced about 30% of the control gait cycle, transient duration $\tau = 200$) that helps avoiding the fall. See Fig. 3 caption. In *a–c*, the *solid curves* are phase advanced compared to the *dotted* control motion data after the perturbation



the phase-advanced responses (Fig. 4) and the phase-delayed responses (Fig. 5), respectively, mimicked well the human stumbling reactions with the lowering and elevating strategies.

Figure 6 summarized results of our systematic exploration of optimal amounts of phase reset for various perturbation phases. The horizontal axis common to the upper and lower panels is the time from the beginning of the gait, representing the impact time, or the gait phase in terms of percentage of one gait cycle, whose origin was set as the beginning of the single-stance phase of the right leg at 7,750 ms, at the impact. The vertical axis is the amount of phase reset examined. When the robot could keep walking despite the perturbation for a given timing and an amount of the reset, the corresponding set of the parameters (grid) for the success gait was marked with a square. Otherwise, no square marks were made, for which the robot fell down for that timing and reset (failed gait). The failed gait shown in Fig. 3 corresponds to the open circle located on the horizontal central line of the upper panel of Fig. 6. Together with Fig. 6 lower panel, it could be confirmed that the impact timing at 9,500 ms was the middle of single-stance phase in which the left foot was in contact with the ground and the right leg was in its swing phase. The phase-advanced gait shown in Fig. 4 corresponds to the filled square with open circle located at the grid (9,500, -800). The filled square with open circle at the grid (9,600, 600) corresponds to the gait with the phase delay reset shown in Fig. 5. One could imagine the functional shape of the optimal phase resetting curve from Fig. 6. That is, a phase resetting curve lying within the squared region provides an optimal response of the robot to every timing of the impact.

In Fig. 6, one could also see that, for the impact at 9,500 ms (right late swing) for example, relatively large amounts of phase advance (from -600 to $-1{,}000$ ms, corresponding to 23–38% of the control gait cycle) could lead to the maintenance of gait against the impact. For this impact timing, intermediate amounts of phase delay (from 200 to 700 ms, corresponding to 8–27% of the control cycle) could also lead to the maintenance of gait.

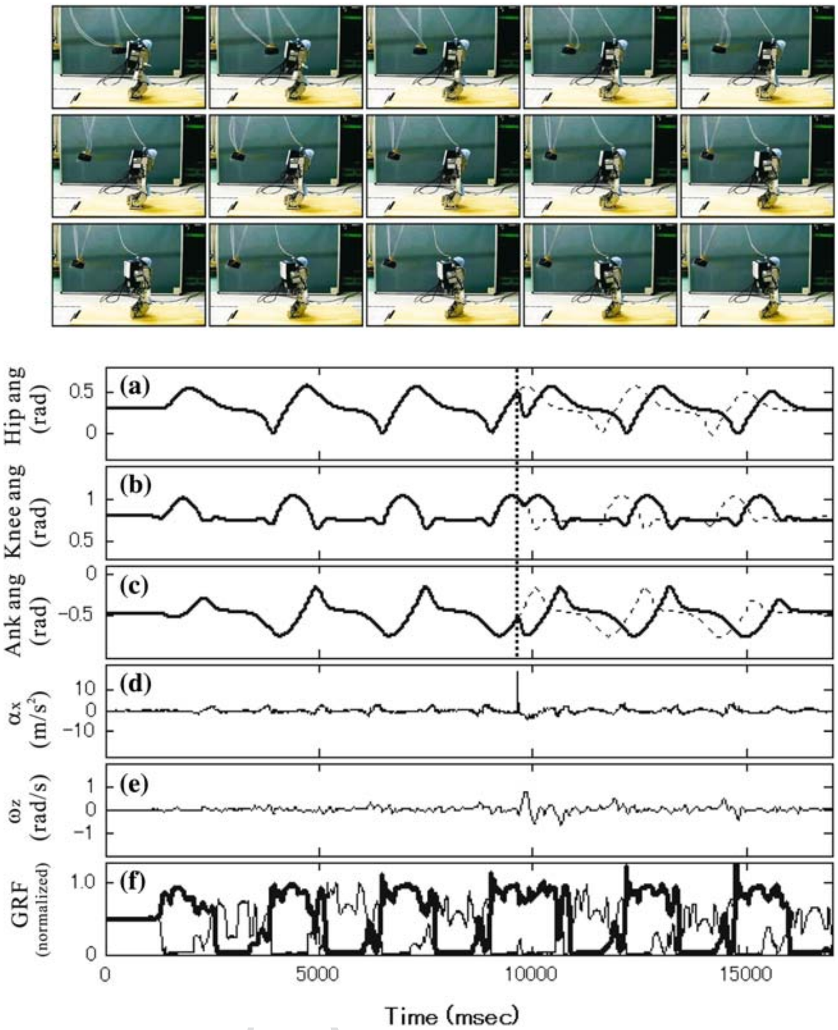


Fig. 5 Response of the humanoid to the impact at $t = 9{,}600$ ms (late right swing) with the phase resetting by the amount of 600 ms (phase delay about 20% of the control gait cycle, transient duration $\tau = 200$) that helps avoiding the fall. See captions of Figs. 3 and 4

That is, for the given impact timing, both the phase-advanced (lowering strategy like) and the phase-delayed (elevating strategy like) responses could avoid a falling. Figure 6 shows that, for the perturbations at the early swing, no or small phase reset was appropriate, and the optimal amounts of phase reset in both advanced and delayed directions increased as the gait phase at the impact increased in the right single-stance phase. See Sect. 4 for these results in comparison with the human gait.

The phase-delayed responses corresponding to the open squares at (8,500, 1,000) and (9,800, 1,000) at the beginning of the double stance in Fig. 6 examined with the transient duration $\tau = 600$ ms. For these cases, the control gait without phase reset could not avoid falling despite that the impact was applied at the double-stance phase. Moreover the phase-delayed responses with $\Delta n = 1{,}000$ ms (38% phase delay) with $\tau = 200$ ms could not prevent the robot from falling. However, the phase-delayed reset with a longer transient duration ($\tau = 600$ ms) could avoid falling, showing that the transient duration for the phase reset was also an important gait parameter determining a modification of gait trajectory when the perturbation was applied. The reason we examined these two cases with the long transient duration was as follows: these two grids, in particular the condition (9,800, 1,000), were located close to the filled-square region for which the phase reset with 200 ms transient led to the success gait. We expected a continuity of this region to larger amount of phase delay. However, it was not the case. That is, the motion of the robot with 1,000 ms phase shift and 200 ms transient was apparently too fast, and the right leg close to the ground contact phase fanned the air rapidly in the backward direction during the resetting motion (see Electronic Supplementary Material Movie 5), and it generated a large forward momentum, leading to destabilization of the posture. It was highly expected that the same amount of phase delay but with a long transient might not generate a large forward momentum and could result in a

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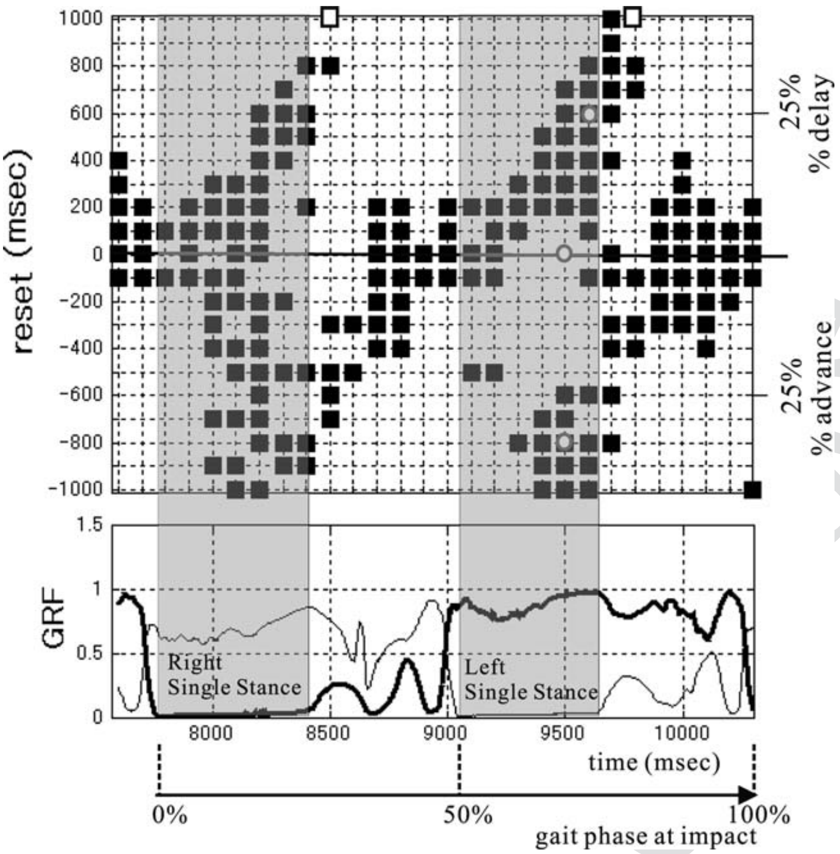

Fig. 6 *Top* Optimal amounts of the phase reset for various phases of the hammer impact. Horizontal axis common to the *upper* and *lower panels* is the time from the beginning of the gait, representing the impact time, or the gait phase in terms of percentage of one gait cycle, whose origin was set as the beginning of the single-stance phase of the right leg at 7,750 ms, at the impact. The vertical axis is the amount of phase reset examined. When the robot could keep walking despite the perturbation for a given timing and an amount of the reset, the corresponding set of the parameters (grid) for the success gait was marked with a *square*. Otherwise, no square marks were made, for which the robot fell down for that timing and reset (failed gait). *Bottom* Averaged GRF acting on the left (*thick curve*) and the right (*thin curve*) foot. GRF was normalized by the total weight of the robot. The failed gait shown in Fig. 3 corresponds to the *open circle* located on the *horizontal central line* of the *upper panel*. The phase-advanced gait shown in Fig. 4 corresponds to the *filled square* with *open circle* located at the grid (9,500, −800). The *filled square* with *open circle* at the grid (9,600, 600) corresponds to the gait shown in Fig. 5. The phase-delayed responses corresponding to the *open squares* at (8,500, 1,000) and (9,800, 1000) were examined with the transient duration $\tau = 600$ ms. See text

reasonable retouch down of the right leg after the reset, leading to a success of the stumbling gait. This expectation was right as summarized in Fig. 6. (See Electronic Supplementary Material Movie 6 for the corresponding gait.)

One could observe in Fig. 6 that the configuration of the squares for the first half of the cycle and that for the latter half cycle was similar but not the same. If the robot gait on our walk way were precisely straight and periodic, these two half cycles would have been symmetrical. However, this was not the case in our experimental setup. For this reason, for the early part of the latter half of the cycle (early right swing), the phase-advanced responses tended to be failed, although we could obtain appropriate amounts of phase-advanced reset for the corresponding phase interval in the first half cycle (early left swing).

4 Discussion

We showed that there exist optimal amounts of phase reset that could prevent the walking humanoid robot from falling against a relatively large impulsive force perturbation in the anteroposterior direction applied at the robot's back. The obtained optimal amounts of phase reset depended on the gait phase (timing) of the perturbation, by which we confirmed that the phase resetting theory developed for the simple gait model on the sagittal plane (Yamasaki et al. 2003a,b) could be extended into the real-world gait as far as examined perturbations in the anteroposterior direction were concerned.

The result shown in this paper could be interpreted as follows. In the cases without phase reset, the perturbation moved the system's state point on the limit cycle outside the basin of attraction of the limit cycle, leading to the fall of the robot. With an appropriate amount of phase reset, a state point relocated by the perturbation outside the basin of the limit cycle of the system without phase reset becomes inside the basin of the limit cycle of the system with phase reset, leading to the prevention of the fall. Such an optimal amount of the phase reset for every examined timing of the hammer impact was identified by trying ten phase-advanced (from −100 to −1,000 ms, corresponding to the phase advance of 4–38% of the control gait cycle) and ten phase-delayed (from 100 to 1,000 ms, corresponding to 4–38% of the control cycle) modifications of the control motion data in response to the detection of the hammer impact.

The result of this study was qualitatively consistent with the ones reported for the perturbed human gait (Kobayashi et al. 2000) and for the differential equation model of human gait (Yamasaki et al. 2003a,b), implying that the phase reset mechanism during gait could be a common and useful strategy for increasing gait stability. It has been discussed that, for human motor control, such a reflex-like response for trajectory modification might be beneficial to maintain desired cyclic movements with low joint stiffness under the influence of feedback transmission delay (Yamasaki et al. 2003a), although the response of the robot examined in this study merely emulated the reflex-like movement using the high-gain local feedback mechanism (i.e., with very high joint stiffness) that could never be realized in the living animals. In the human stumbling reaction, two strategies have been clarified (Schillings et al. 1999; Forner Cordero et al. 2003). Those include the elevating strategy occurred for the stumble perturbation at early swing, and the lowering strategy at late swing. The elevating and lowering strategies are, respectively, consistent with the delayed and advanced phase reset responses as shown in Yamasaki et al. (2003a,b). In the current robot experiment, for most of the perturbation phases for which the phase reset could avoid the falling, there was a tendency that both phase-advanced and phase-delayed responses, if appropriate, could avoid the falling, implying that there is a freedom for "the controller" to choose one of these two resets. It is worthwhile to associate this result with the fact that, when the perturbation is applied at a certain range of the mid swing in human stumbling reaction, both the elevating and lowering strategies could occur (Schillings et al. 1999; Forner Cordero et al. 2003). Based on this result, Schillings et al. (2000) made the following discussion: "The same initial reaction of the two strategies possibly provides the CNS sufficient time to integrate information obtained by various sensory receptors and supraspinal sources to make an appropriate decision about the final behavioral strategy." Delayed lowering strategy at early swing, in which first elevating-like response appears right after the perturbation and then switches to the lowering strategy, could also be related to this discussion. The result of the robot experiment suggests the following scenario: for a certain range of the perturbation phases, both the phase-advanced and phase-delayed resets could avoid the fall in the sense of the mechanical stability during human gait, but the response might not be predetermined at the onset of the perturbation. The CNS, as the phase controller in a sense of the current study, can choose one of them based on the various integrated sensory information.

Let us discuss the transient duration used for the phase reset. The transient duration, in which the phase reset was progressively achieved, might be an influential determinant whether or not the robot with the resetting gait trajectory could avoid a falling. In the human gait and the simulated human gait experiments (Yamasaki et al. 2003a,b), in which the perturbation applied at the lower right leg by an impulsive tug from the behind was used, it was shown that the phase advance with relatively long transient, 30% of the gait cycle (∼300 ms), was optimal for the late swing perturbation, and the phase delay with short transient, 5–10% (∼100 ms) for the early swing perturbation. The transient duration 200 ms used in the current humanoid experiment was about 8% of the gait cycle ($T \simeq 2,600$ ms), and it was in the latter short transient range. Although only two cases with the long transient (600 ms) responses were examined in this paper, they exemplified that perturbed gaits with a selected amount of phase reset could be different (success or fail) depending on the transient duration. One important factor that caused the difference could be the inertia force (momentum) generated by the motion during the phase reset. That is, a large amount of phase reset with a short transient duration results in a rapid movement and thus generating a large inertia force, but that with a long transient does not. Effect of such an inertia force on the gait stability against the perturbation is phase dependent. That is, the inertia force caused by the motion during the reset could counterbalance or foment the momentum generated by the perturbation. The effect of this inertia force on the gait stability must

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be evaluated together with the momentum generated by the ground reaction force acting on the body during or after the phase reset. For the two cases described in this paper, it was visually apparent that the large inertia force generated during the phase delay response fomented the forward momentum, leading to the gait destabilization. We thus tried a long transient duration to reduce the amount of inertia force, and obtained two cases exemplifying a role played by the transient duration of the phase reset. For the sake of completeness in the current study, we should have varied systematically the transient duration as in the simulated gait. However, the humanoid experiment with the hammer impacts over hundreds of times was too tough to achieve for the machine. The systematic modification of the transient durations and analyses based on mechanical dynamics could be topics for future research.

Forner Cordero et al. (2004) discussed relations between physical constraints on possible hip torques compensating the forward trunk motion and swing speed during human gait responses in the first double-stance phase just after the perturbation simulating a stumble. They claimed that the lowering (and delayed lowering) strategy for the late swing perturbation resulted in shorter step lengths and had lower hip torques due to the physical constraints, implying a difficulty in compensating the forward trunk motion in the first double-stance phase. Thus, one more or several compensation steps are needed. This is consistent with the long transient duration for the phase-advance responses shown in Yamasaki et al. (2003a,b), in which early part of the second step of contralateral swing leg after the quick touch down of the perturbed foot is still in the phase resetting transient, and it is accompanied by a quick motion. In the current humanoid experiment, the phase-advance responses with the short transient for the late swing perturbation could avoid the falling. One reason for this discrepancy could be a relatively long period of the humanoid gait ($\sim$2,600 ms) and slow walking velocity. That is, forward momentum in the control and the perturbed gait was small. Hence, the lowering strategy with the phase-advance response and thus short step in our robot experiment did not necessarily encounter the difficulty in compensating the forward trunk motion in the first double-stance phase. In this sense, it is expected that shorter transient duration for the lowering strategy might be enough for slower gait speeds, and a human gait experiment will be able to confirm this expectation.

Regarding quantitative aspects of the optimal phase reset, the optimal amount of phase reset in the current study for the robot was different from the ones obtained for the human and simulated gaits. This difference might be due to differences in the way of perturbation, in the mechanical and physical characteristics (mass, inertia, etc.) between the human and the robot, as well as in the way of determination of the transient duration. The latter two factors largely affect the trajectory of the zero moment point (ZMP) during gait as discussed below.

Zero moment point is defined as “a theoretical point” such that the momentum caused by the external force (the ground reaction force for gait) applied to ZMP balances with other forces (the inertia and centrifugal forces) that will be generated if the robot performs a prescribed motion. The ZMP stability criterion (Vukobratovic et al. 1990) has been used to prescribe an unperturbed gait trajectory and to modify the gait trajectory in response to a perturbation in order to generate a desired compensating gait trajectory. It examines, prior to the gait execution, if ZMP trajectory for the prescribed gait trajectory is always inside the foot support area and the prescribed trajectory can be a solution of the equation of motion of the robot. The modification of the gait trajectory is carried out in response to the perturbation. To this end, after the perturbation, the foot contact times and their placements and the modified desired ZMP trajectory for the transient duration are determined, and then the modified joint trajectory is determined so that the ZMP of this gait coincides with the modified desired ZMP. Note that there exist infinitely many joint trajectories that are accompanied with the single ZMP trajectory, implying that the determinant of a specific joint trajectory is an ill-posed problem. Note also that, computationally, the equations of motion of the robot are usually utilized to solve the ill-posed problem. In this way, the determinations of the modified desired ZMP trajectory and the corresponding joint trajectory can specify the modified gait trajectory. When one employs a strategy to compensate the perturbation using an appropriate modification of the trunk movement (hip joint trajectory) and/or modification of the total ground reaction force vector without modifying the foot contact times (but maybe with modifying its location), the resultant trajectory may be able to avoid a falling, but in this case the gait does not show the phase reset. When a strategy that modifies the step length in time (and maybe also in spatial location) to compensate the perturbation is employed with or without considering ZMP criterion, the resultant gait may always be accompanied with the phase reset. It is an open problem, for human gait, whether the phase reset is just a consequence of the modification of the foot contact times and placements that are determined based on the ZMP criterion or the phase reset causes the modification of the foot contact times and placements during human perturbed gait, or even both of them are concerned. See the work

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by Honda (Hirai et al. 1998) for an integrated example of a humanoid gait control, in which the role played by the foot landing position control (landing timing control seems to be made implicitly) is considered to be rather limited for stabilizing the gait.

If the CNS concerns the ZMP to determine the modified gait trajectory, regardless of the use of phase reset, the CNS should concern the equations of motion, implying the necessity of an internal model of the body dynamics in the CNS. In this study, the optimal amount of phase resets were determined by examining various values as many as possible without using the ZMP stability criterion. This may correspond to, for the CNS, to construct a look-up table relating the perturbation timing and the optimal amount of the phase reset. This is possible when a way to apply a perturbation (such as the hammer impact intensity, direction, the impact location of the robot's body, etc, in this study) is fixed. Since the human gait is robust and adaptive against various types of perturbations, it is not possible to consider a look-up table as a feasible physiological mechanism to trigger a stumbling reaction in humans. Thus, usage of the internal model of the body dynamics to determine the modified gait trajectory is expected.

Other lines of research have shown that biped robot stability can be achieved without the application of the ZMP stability criterion (e.g., McGeer 1990; Collins et al. 2005; Van der Linde 1999), where natural dynamics of inverted-pendulum-like body of the biped robot without active joint torques or with less amount of active torques can realize stable biped gaits along a down slope or on a level ground. The stability of such passive gaits does not explicitly address prescription of desired gait trajectory and modification of it in response to perturbations, but physical parameters of the body links and appropriate viscoelasticity of joints determine the gait trajectory "dynamically" as a limit cycle. Although the trajectory modification in response to perturbations is achieved only passively during such passive gaits, the state point of the robot asymptotes to the limit cycle if it is inside the basin of the limit cycle with some amount of phase reset. The responses shown in this study were similar to this, but the modification of the gait trajectory performed in this study was not passive, and the gait phase was actively reset so that the state point after the perturbation became inside the limit cycle. Revealing neural mechanisms that are responsible for the active reset could be an important issue for future research. Possible candidates for the mechanisms are, for example, the involvement of the internal model of gait dynamics as mentioned above, and active reflex control of the muscle impedance among others.

Several previous studies have implemented phase resetting mechanisms to biped robots in order to increase gait stability (e.g., Tsuchiya et al. 2003; Nakanishi et al. 2004). Tsuchiya et al. (2003) proposed a biped gait control scheme using coupled phase oscillators, and introduced feedback pathway directly from a foot sensor to the corresponding oscillator to reset its oscillation phase. In the study by Nakanishi et al. (2004), interconnections among oscillators, as well as feedback gains to the coupled oscillators inducing the phase resetting, were determined through learning processes. Both cases show that the phase resetting mechanism contributes to increasing gait stability against environmental perturbations. It is worthwhile to emphasize that intensities of the examined perturbations in those studies, and thus the amounts of phase reset induced, were relatively small compared to the ones concerned in the present study. It is likely that realizing phase-dependent resetting with a large amount using nonlinear oscillators might not be easy, since the amount of phase reset is determined by both intrinsic dynamics of the oscillator and characteristics of feedback signals. Moreover, in those studies, only foot contact events were used to trigger phase resetting of the oscillators, whereas it is not the case for the present study and in human gait response to the perturbation examined in Kobayashi et al. (2000). Corrective modulation of the gait trajectory including the resetting triggered by the foot contact seems to work well for phase-advanced case, which would be usual if a swing foot is forced to make an early contact. When phase-delayed responses corresponding to the stumbling with elevating strategy are optimal to avoid falling, a resetting triggered at the first foot contact after the perturbation might be too late, and a resetting immediately after the perturbation, before the foot contact, is required.

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