Review:

NANBA Walking Robot (JIZAI Movement of Physical Body Using State Transition with Instability)

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The effectiveness of transmitting force by using undulation is well known, but it takes time for the whip to flex and then sequentially transmit force. An example of using undulation is a whip whose tip movement exceeds the speed of sound. The whip-like motion principle requires that the user firmly plant the feet on the ground – a position that may lead to physical damage. Experts note that the load on different parts of the body is lowered by using the entire body appropriately. Using the term "nanba" symbolically to indicate body movement that does not use twisting, undulation, or the firm planting of the feet and that exerts minimal load on the joints, we investigate movement of a bipedal robot based on state transitions that utilize instability. Speed and robustness result when a state (posture) is created instantaneously so that no blockage by the body occurs and transitions from state to state are made in a single step.

Keywords: humanoid biped robot, distributed control of physical body, state transition, robustness, subsumption architecture

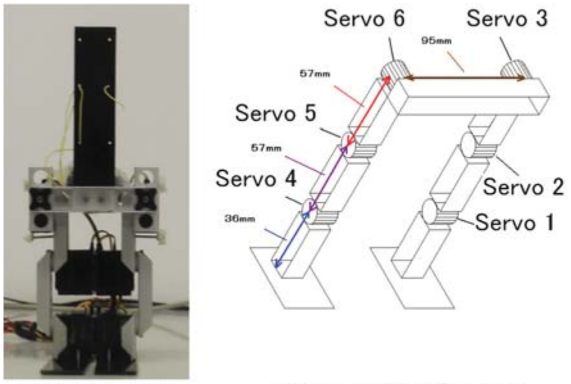
1. Introduction

High expectations are placed on a diversity of robotic technology applications in domestic living, public service, and the medical and welfare fields, but no specific applications or technological possibilities that meet market expansion have been clarified [1]. The conventional robots that pursue task accuracy, speed, and efficiency recognize the external environment, construct an internal model of this environment, draw up action plans, and execute actual tasks. Robots based on such serial processing will, however, fail to execute the final task if an error occurs in the process. The entire system must also be reconstructed from scratch when additional functions are added [2–5].

Humanoid robots, considered to be at the forefront of robotic technology, prevent falling, for example, while executing bipedal locomotion (walking) by exerting force against gravity, which acts to brake forward thrust, but this is wasteful in energy consumption, exerts considerable loads on joints, requires intricate complex control, and is vulnerable to external disturbance and susceptible to falls [6].

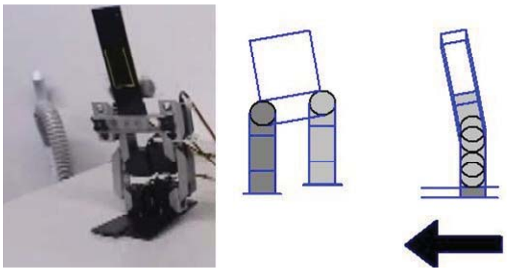
Conventional bipedal robot walking is based on "pushing with the sole against the ground, controlling falling, and landing in an ideal position." This means controlling the robot's center of gravity and zero moment point (ZMP), e.g., [7]. A walking mode that resists gravity, however, acts to brake forward thrust and is wasteful in energy consumption, exerts considerable load on joints, requires intricate complex control, and is vulnerable to external disturbance. If we employ the novel principle of walking in which movement is created by unstable postures – the reverse of conventional ZMP control – it is possible to create a bipedal robot capable of "nanba" walking and running, instantaneous directional changes that we call nanba turning, and nimbly using stairs. Such robots also can autonomously avoid the impact of falls, e.g., when suddenly pushed from behind by an external disturbance and recovering from such falls while also quickly avoiding moving obstacles suddenly appearing in their paths [6, 8–12]. Such nimble flexible movements cannot, however, be achieved by conventional linear dynamics and linear control, which is based on brute control. When a robot is about to fall forward, an unexpected action may be necessary, such as falling on one's bottom. A robot incapable of breaking falls or recovering autonomously is like an automobile without brakes – out of control and uncontrollable.

Nanba walking and running by a bipedal robot, Genbe, is based on "falling in the intended walking direction, and stepping – moving the foot forward – in the direction of falling." The robot's name, Genbe, comes from a legendary messenger of the Edo period (1603–1868). The legendary Genbe was said to have run the 300 km distance between Edo (modern name Tokyo) and Sendai in a single day [13]. In this study, the term nanba, which expresses a mode of physical movement control, is used not in its strict meaning but rather symbolically to indicate movement that does not create a large load on joints, doing so by avoiding twisting undulating movements, or planting the foot in place on the ground.

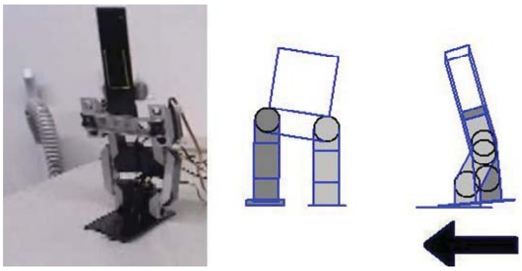


(a) Genbe No.2 (b) Legs with 6 freedom

Fig. 1. Biped Robot Genbe No.2.



(a) State 1



(b) State 2

Fig. 2. Fundamental states of nanba walking by Genbe No.2 with 6-DOF legs.

2. NANBA Walking and Running Based on Distributed Control of the Physical Body in Martial Arts

In the simplest configuration, six degrees of freedom (DOF) are given to Genbe's lower limbs (Genbe No.2; height 300 mm, weight 550 g, **Figs. 1** and **2**). In forward leaning posture, nanba walking is based on

1) state 1: when the body leans to the right, the left leg is lifted, and

2) state 2: when the left foot moves forward, the body spontaneously leans left and forward to bring the left foot into contact with the ground. States 3 and 4 are opposite movements in which the body leans left and walking is executed by repeating this sequence of movements. Active use is made of falling forward when the foot is raised.

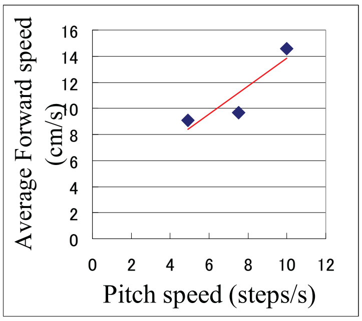
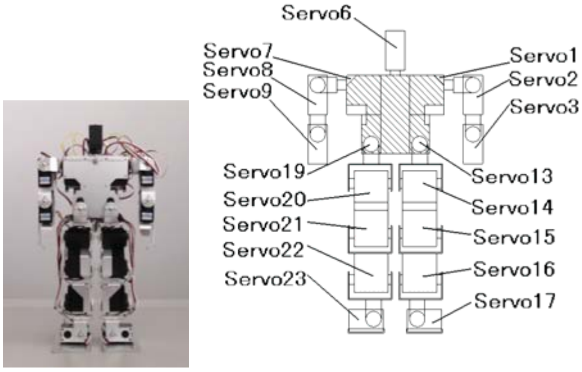


Fig. 3. Forward speed vs pitch speed of biped robot Genbe No.2 with 6-joint legs.



(a) Genbe No. 4 (b) Servomotors of 10-DOF legs

Fig. 4. Humanoid biped robot utilizing instability.

Figure 3 shows the relation between forward speed (ordinate) and pitch speed of the legs, shown in the abscissa. Desired forward speed is achieved while falls are avoided by combining rotational angular servomotor speed and the angles of upper-body and knee joints. As long as torque is sufficient to lift the legs, forward speed increases proportionally with pitch speed of the alternating legs.

When Genbe's lower limbs are given 10 DOF, as shown in **Fig. 4** (Genbe No.4: height 34 cm, weight including batteries 1.2 kg), the robot walks while using the ankles and simultaneously keeping the upper body (head) upright [6, 8].

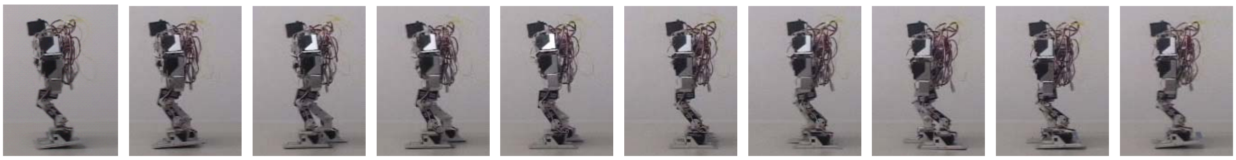
Nanba walking naturally shifts into running when both the robot's forward leaning angle and pitch speed increase.

Figure 5 shows nanba running by "Japanese old martial arts researcher Yoshinori Kohno." **Fig. 6** shows running (the nanba dash, 18 cm/s) of Genbe No.4 (0.3 seconds, each foot taking one step), corresponding to Kohno's running. Pitch speed is six steps a second. Nanba running loosens the body appropriately by eliminating body blockage. High speed is achieved by switching instantaneously from one state to another [13]. In the same manner as the walking principle in **Fig. 2**, Genbe No.4 achieves high speed and power by transitioning from state 1 to state 2 by utilizing instability as shown in **Fig. 7**.

Genbe's nanba walk is simple bipedal walking that uses the limit cycle attractor formed between the robot and the

(1) t = 0.000 s (3) t = 0.133 s (5) t = 0.266 s (7) t = 0.399 s (9) t = 0.532 s (11) t = 0.666 s

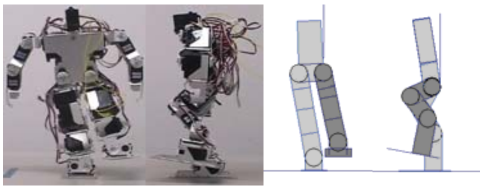
Fig. 5. Nanba walking and running of Yoshinori Kohno.



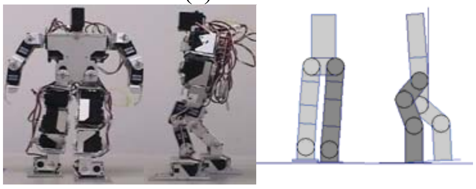
(a) 0.000s (b) 0.033s (c) 0.066s (d) 0.099s (e) 0.133s (f) 0.166s (g) 0.199s (h) 0.233s (i) 0.266s (j) 0.299s

(a) nearly state 1 **(c) state 2** **(f) state 3** **(h) state 4**

Fig. 6. Emergence of simple self-sustained humanlike robust nanba running by humanoid biped robot Genbe No.4.



(a) State 1



(b) State 2

Fig. 7. Fundamental states of nanba walking and running of Genbe No.4 with 10-DOF legs.

ground by the force of falling. Although the period and amplitude (stride) of the walking cycle are roughly periodic, such factors as servomotor load and slippage between the foot sole and ground subtly affect the time required to lift the leg and the length of the stride, subtly changing the period and stride and displaying complex chaotic behavior. Limit cycles are robust against unexpected external disturbance and are flexible enough to respond to situational change [6].

Figure 8 shows robot states in ascending stairs. When the Genbe assumes the state 2 posture while in state 1, it falls forward due to the force of falling so that the left foot begins its next step. When the robot assumes the state 3 posture while in state 2, the right leg is lifted as the left leg rests simultaneously during the next step. Genbe climbed one step of the five in this experiment nimbly and in about one second, exactly as though insufficient servomotor torque was not an issue.

Figure 9 shows an actual trial. Genbe lifts its legs high, leans considerably forward, and executes dynamic movement using the entire body. Genbe descends stairs similarly (description omitted here due to space limitations). For robots, descending stairs is much easier than ascending them [14].

Figure 10 shows the instantaneous turn principle based on instability. Transitioning from state 1, in which the left leg in front carries the weight as Genbe leans forward, to state 2, in which the right leg is in front, Genbe turns instantaneously 180° to the right in the same spot, as shown in **Fig. 11** [15].

3. From Whip-Like Body Control to Distributed Physical Body Control

According to Kohno [13], a human being intending to exert force usually presses the foot against the ground and, using this as a base, adjust body posture sequentially starting from the knees and hips and going to the waist, back, chest, shoulders, elbows, and hands. In other words, although the human being prepares as quickly as possible to exert force in some direction, a force wave is transmitted through the body similar in movement to an undulating whip or as in the domino effect. This state creates a slight delay (*tame*), and although necessary force is potentially generated using the body in the manner of an undulating whip, this requires time. In Kohno-style nanba running, high speed is achieved by controlling the body to eliminate blocks and suddenly shifting from one state to another [13, 16]. The Jamaican sprinter Usain Bolt, who holds world records in the short-distance sprint, displays body control approaching one in which twisting, undulating, and planting the feet in place are avoided but even Bolt damages his lower back, which prevents him from taking part in competition.

We use the term nanba symbolically as a "visual aid" for expressing movement that does not create a large load on joints [16].

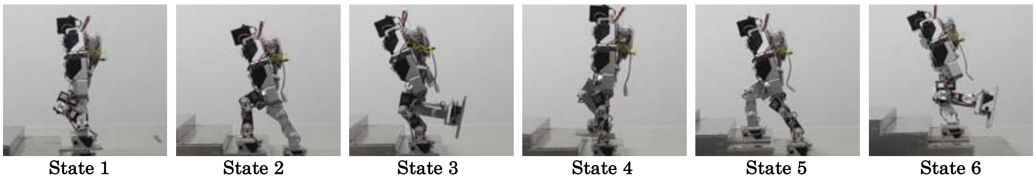


Fig. 8. Six states of Genbe No.4 with 10-DOF legs for ascending stairs based on instability.

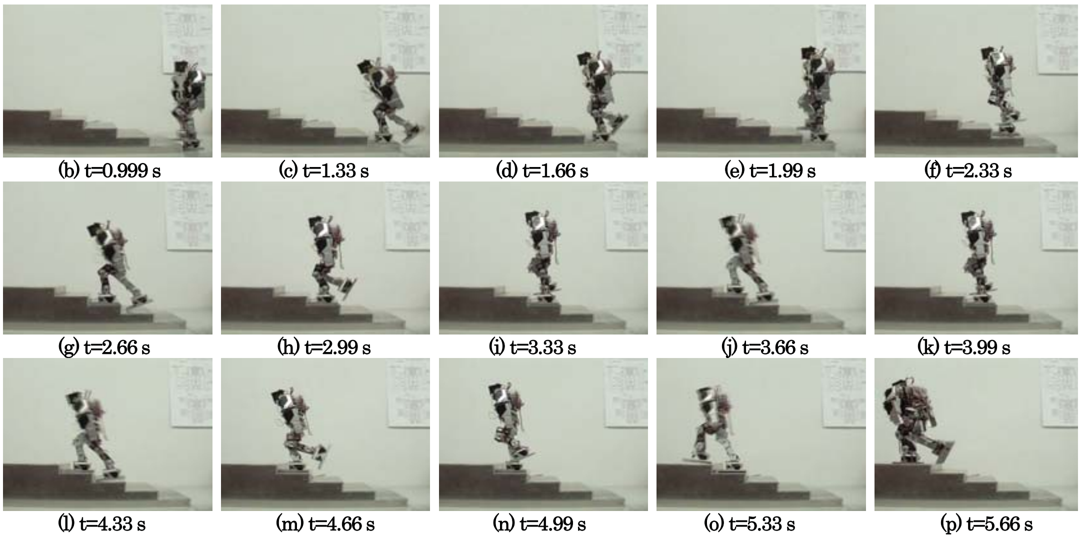
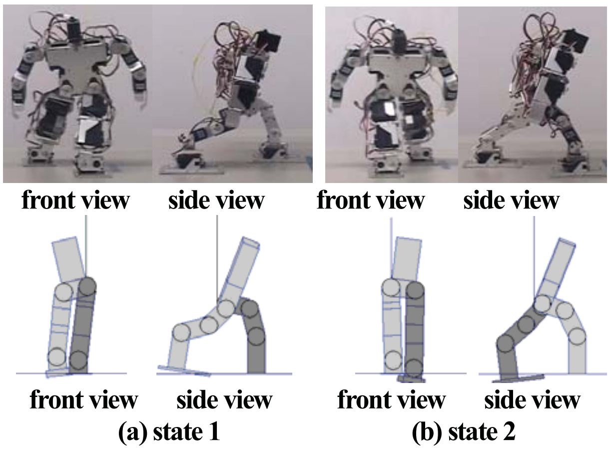

(b) t=0.999 s (c) t=1.33 s (d) t=1.66 s (e) t=1.99 s (f) t=2.33 s
(g) t=2.66 s (h) t=2.99 s (i) t=3.33 s (j) t=3.66 s (k) t=3.99 s
(l) t=4.33 s (m) t=4.66 s (n) t=4.99 s (o) t=5.33 s (p) t=5.66 s

Fig. 9. Genbe No.4-2006 with 10-DOF legs ascending stairs using instability.



(a) state 1 (b) state 2

Fig. 10. Two states of 180° nanba turns.

Figures 12 and **13** show the bipedal robot with ten-jointed legs stepping to the right.

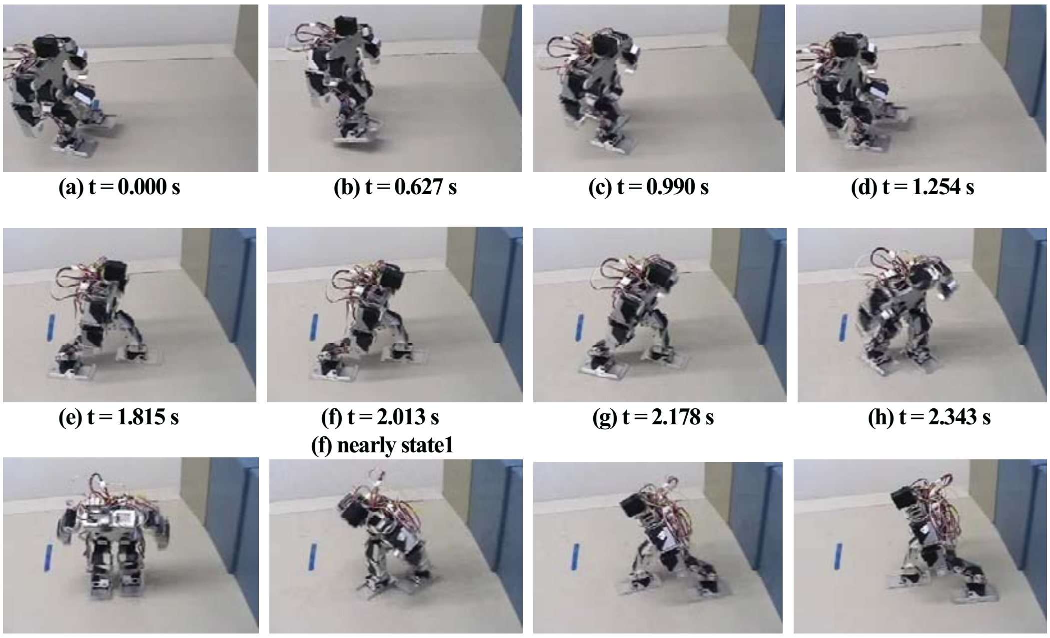
Figure 12 shows the robot sidestepping by kicking the ground with its support leg while movement is generated by state transition from state 1 to state 2 in **Fig. 14**.

Figure 13 shows a sidestep using very little kicking at the ground generated by transitioning from state 1 (unstable) to state 2 (stable) in **Fig. 15**. To sidestep to the right, the right knee is bent slightly and the right leg is lifted and moved to the right, causing the body's center of gravity to shift to the right. The weight of the body is thus removed from the support point (left foot) as much as possible, while the force of falling moves it sideways to the right. All joints start moving simultaneously in parallel, which ends simultaneously with postures of state 1 or state 2. **Figs. 12** and **13** show sideways movement to the right, with the notable difference that the upper body leans in opposite directions.

Figure 16 shows former top-ranking tennis player Ken Rosewall displaying a flowing side step as he executes a backhand stroke [17]. Note his graceful animal-like natural movement. The robot movement in **Fig. 13** gives a clue to why Rosewall's movements are so graceful.

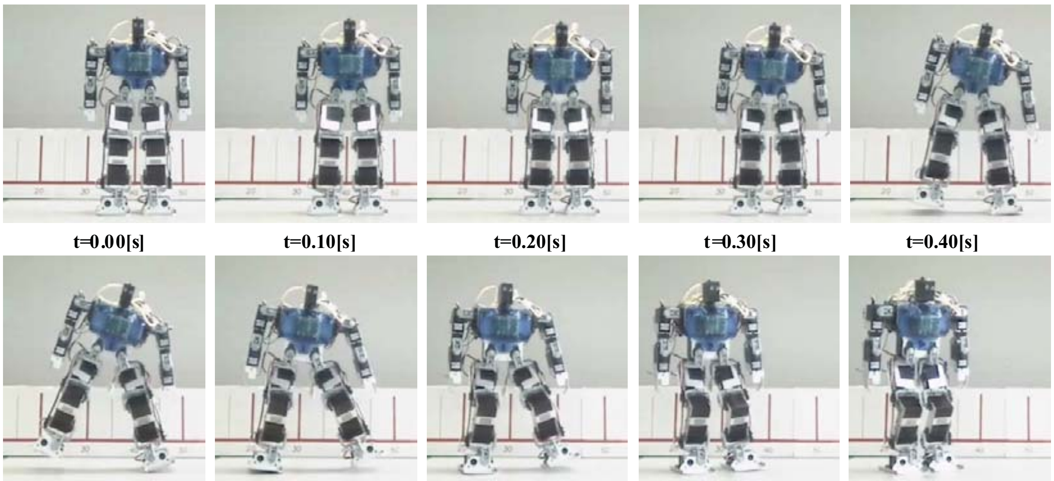
4. Control of Excessive Drive Force and State Transition Based on Instability

Figure 17 shows an example of nonlinear control based on the state transition using instability that we propose. The movement in **Fig. 13** is also such an application and extension resembling that in **Fig. 17**. We use the example of **Fig. 17(a)**, which shows an oscillating second-order element of mass M, which hangs on a string, to explain the mechanism of nonlinear control based on the state transition using instability. Support point A, from which mass M hangs is moved step-wise for distance AB to the position of B. Mass M then becomes a pendulum, swinging passed a point directly beneath B and momentarily stopping at the far end of its swing. At this time, the support point is moved simultaneously step-wise for distance BD from B to D so mass M once again becomes



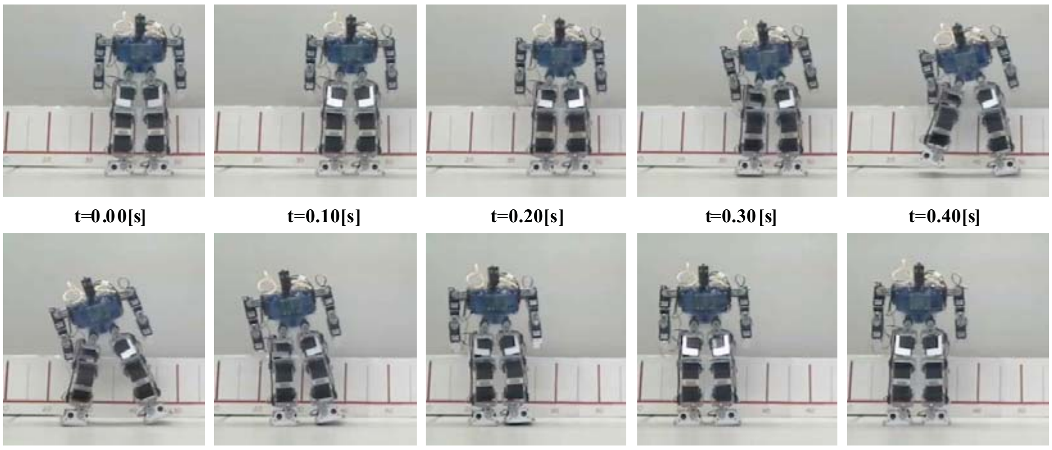
(a) t = 0.000 s
(b) t = 0.627 s
(c) t = 0.990 s
(d) t = 1.254 s
(e) t = 1.815 s
(f) t = 2.013 s
(f) nearly state1
(g) t = 2.178 s
(h) t = 2.343 s
(i) t = 2.508 s
(j) t = 2.673 s
(k) t = 2.838 s
(l) t =3.003 s
(l) nearly state2

Fig. 11. Nanba turn based on distributed body control requiring approximately only 1 second to turn 180°.



t=0.00[s]
t=0.10[s]
t=0.20[s]
t=0.30[s]
t=0.40[s]
t=0.50[s]
t=0.60[s]
t=0.70[s]
t=0.80[s]
t=0.90[s]

Fig. 12. Right stepping using left leg to kick ground (250 fps).



t=0.00[s]
t=0.10[s]
t=0.20[s]
t=0.30[s]
t=0.40[s]
t=0.50[s]
t=0.60[s]
t=0.70[s]
t=0.80[s]
t=0.90[s]

Fig. 13. Nanba sidestepping by Genbe using low active power. Right stepping without using left leg to kick ground (250 fps).

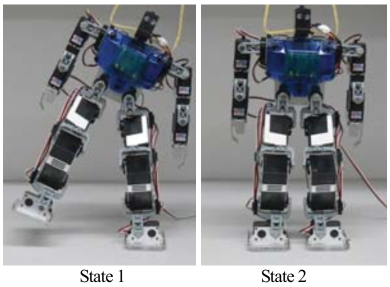


Fig. 14. Two states of right stepping using left leg to kick ground.

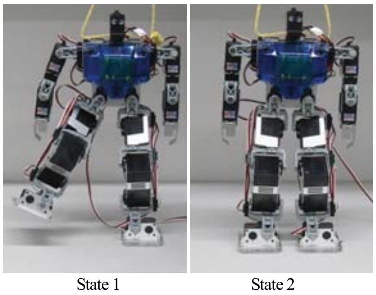
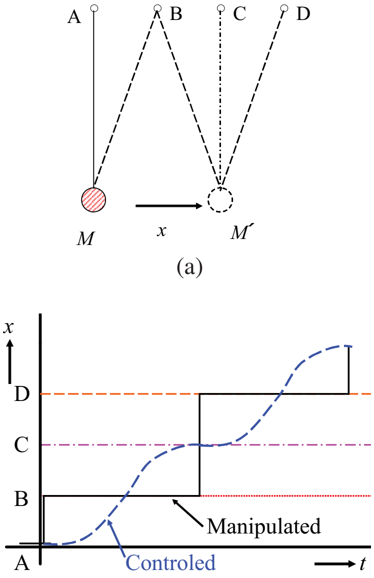


Fig. 15. Two states of right stepping without using left leg to kick ground.

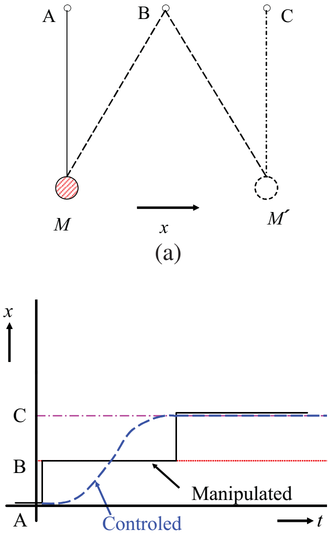
Fig. 16. Side stepping without kicking during backhand stroke by K. Rosewall [17].



(a)

(b)

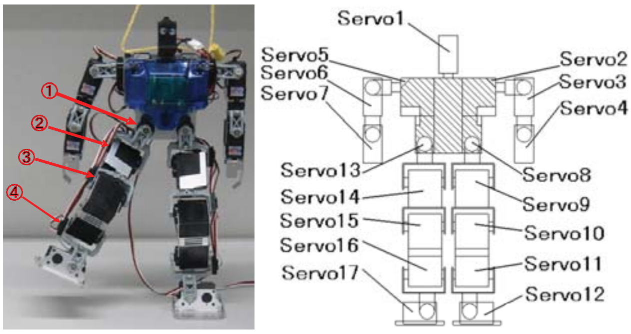
Fig. 17. Proposed nonlinear optimal control applied to humanoid biped robot walking.



(a)

(b)

Fig. 18. Example of nonlinear optimal control by Rufus Oldenburger.



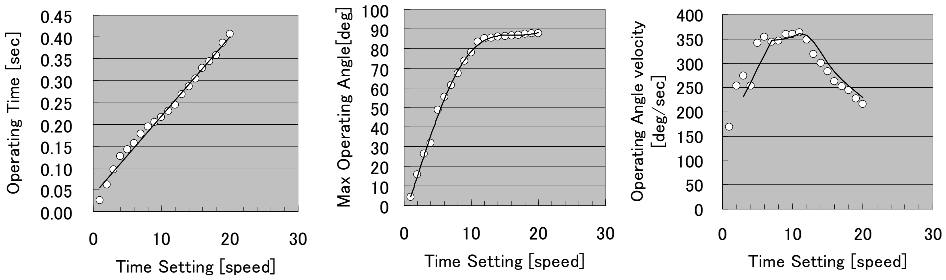
(a) (b)

Fig. 19. Servomotor configuration and state of right stepping using instability without ground kicking.

a pendulum. The mass is moved forward by repeating these oscillations – a limit cycle of self-excited oscillation in which step-wise movement of the support point provides the energy source. The manipulated variable is switched at the instant velocity dx/dt of mass M is zero, as shown in **Fig. 17**. To make a sudden stop, the response to the sudden change in the target value is minimized based on the nonlinear optimal control principle, shown in **Fig. 18** [18, 19].

Speed of travel is changed as needed by changing step lengths AB and BD or by changing the string length. By moving to point C, where mass M stops after a set wait, travel forward at a slower speed is also possible.

Figure 19 shows the robot servomotor configuration in **Figs. 12–15**, with the robot assuming the state 1 posture (unstable) without kicking the ground. The state (posture or form) is created by simultaneously driving hip motor ① and other motors ②–④ by distributed control. All motors are rotated by relative angular displacement for the same time length simultaneously. In **Fig. 13**, the transition



(a) (b) (c)

Fig. 20. Measured operating characteristics vs operating time setting for 90° target operating angle.

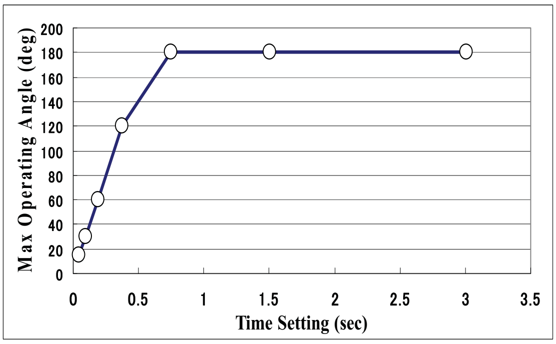
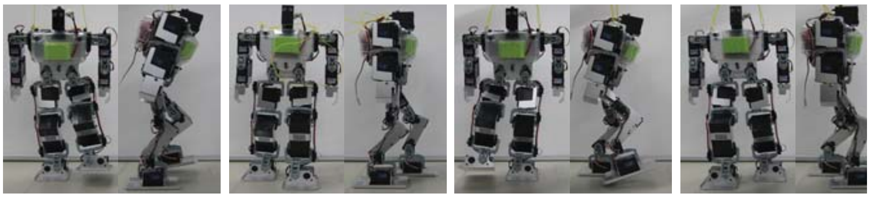


Fig. 21. Measured operating characteristics vs operating time setting for 180° target operating angle.



State1 **State2** **State3** **State4**

Fig. 22. Four states of nanba walking and running by biped robot with 10-DOF legs (Genbe No.4-2007).

from unstable state 1 (0.40 s) to stable state 2 (0.70 s) is made in 0.3 seconds.

Figure 20 shows the measured dynamic characteristics of servomotor KRS-788HV used in the robot, that is, measurement when the relative target angular displacement transition was set at 90°, as plotted against different time settings (speed), shown on the abscissa, where **(a)** is operating time, **(b)** maximum operating angle, and **(c)** operating angular velocity. When time is set longer than 12 units (0.25 s), the motor rotates 90° for an arbitrary time. At time settings of fewer than 12 units, however, it is unable to turn 90°. If the program is executed to make a 90° rotation with a time setting of 3 units (approx. 0.1 s), for instance, the motor rotates only 25° due to insufficient torque. **Fig. 21** gives a program implementation example of rotation at different time settings in which the relative angular displacement of the shoulder, servo 2 in **Fig. 19**, lifts or lowers the arm 180° from lowered to the upper. This shows that the arm is rotated a full 180° as long as the time setting is longer than 0.8 s.

Figure 22 shows states involved in nanba walking and running. By making the robot lean forward at a deeper angle and increasing pitch speed, walking shifts to running. In state 1 (unstable), Genbe leans forward and raises its left leg while its body has shifted to the right. State 2 (stable) is when the left leg contacts the ground. States 3 and 4 are the equivalent of states 1 and 2 with sides reversed. Genbe moves forward by transitioning sequentially among the four states. When Genbe makes the transition from states 2 to 3, it falls forward. By shifting to stable balanced state 4 before it falls over, Genbe walks without falling. Travel speed is chosen at will by setting suitable joint angles (postures) and time settings.

Figure 23 shows Genbe when only part of the program related to transitioning from statically stable state 2 to statically unstable state 3 in **Fig. 22** is implemented. In state 3, which is unstable, Genbe falls forward. It falls down if it remains in this state. By transitioning to statically stable state 4 before it actually falls, Genbe avoids falling and continues walking.

Figure 24 shows the results of running (time-series photography of two steps) of Genbe (height 340 mm,

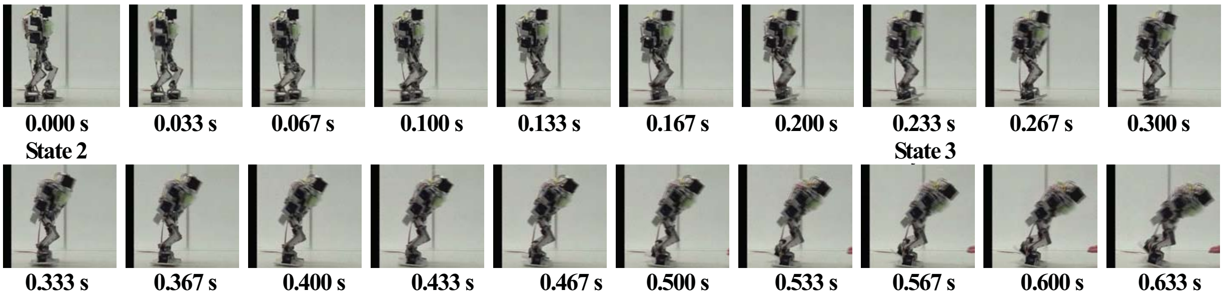


Fig. 23. State transition from state 2, statically stable, to state 3, statically unstable, falling to the ground.

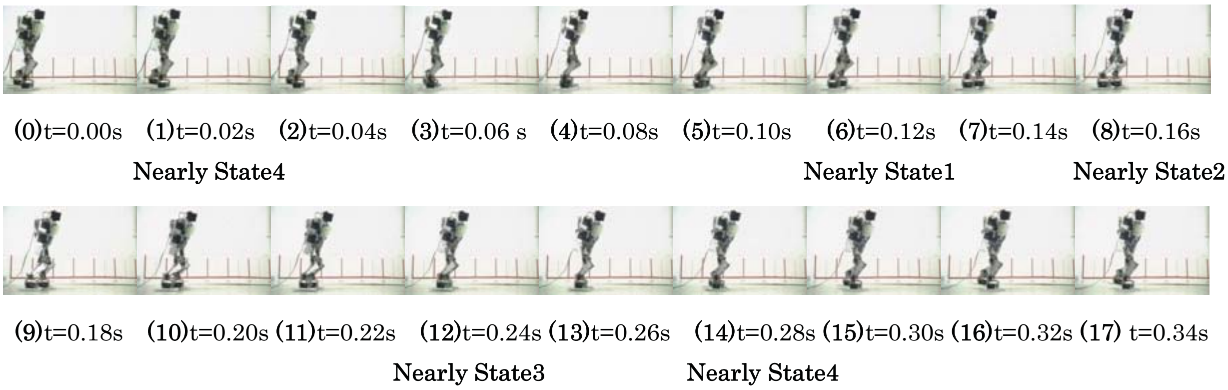


Fig. 24. Nanba dash 36.5 cm/s, 6.58 steps/s of biped robot (Genbe No.4-2007), taking only 0.3 seconds for 2 steps.

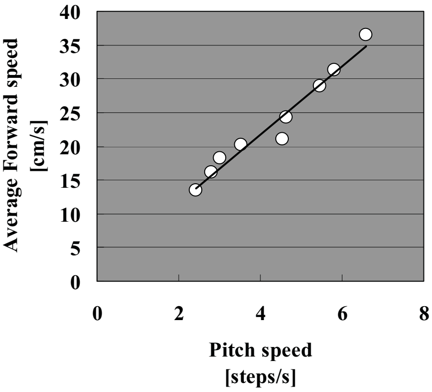
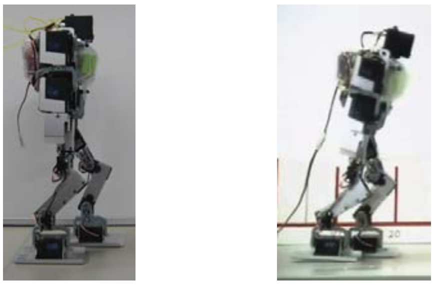


Fig. 25. Biped robot forward speed vs pitch speed.



(a) State 2 in program (b) Nearly State 2 actually

Fig. 26. Difference between program states and actual movement.

weight 1.3 kg) when time settings for states 1 and 3 (**Fig. 22**) are set at 3 units and time settings for states 2 and 4 are set at 4 units using dynamic servomotor characteristics (**Fig. 20**). Pitch speed was 6.58 steps/s and speed moving forward was 36.5 cm/s.

Figure 25 shows measurements of forward speed (the ordinate) plotted against walking pitch speed (steps/s; the abscissa). It shows results when posture angle data (states) were kept constant while the time setting was changed, i.e., the speed of servomotors was changed. Forward speed increased proportionally with pitch speed.

Figure 26 compares **(a)** the posture of state 2 given by the software program and **(b)** posture in actual running shown in **Fig. 24** corresponding to state 2. In high servomotor speeds, i.e., time settings of 3 and 4 units are chosen in actual running, the feet are not raised sufficiently due to insufficient torque and strides become narrower, meaning that movement is not programmed, yet Genbe ran without falling.

Figure 27 shows the measurements of forward leaning angles plotted against the servomotor time setting. When the time setting is 5 or less, the shorter the time setting, the more the leaning is pronounced. **Fig. 28** shows stride length plotted against the time setting in which stride length was calculated from measured travel distance (averages of three trials and their standard deviations). Note that stride is not reduced even when a time setting is short and remains about the same regardless of whether time setting is short or long. The fact that forward speed is

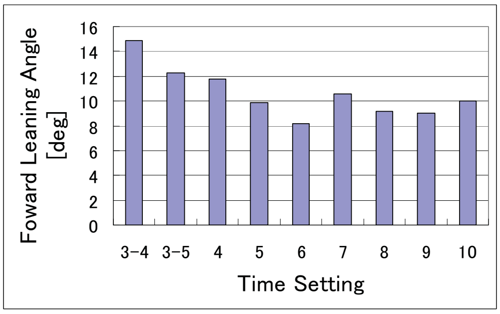


Fig. 27. Forward leaning angle vs time setting.

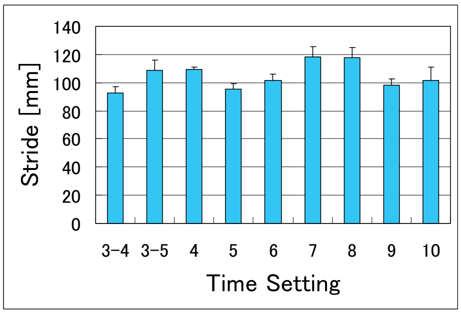


Fig. 28. Stride vs time setting.

Fig. 29. Robustness of humanoid biped robot Genbe running on ice and snow and taking 9 steps in 1.50 seconds.

proportional to pitch speed in **Fig. 25** means that stride is unchanged.

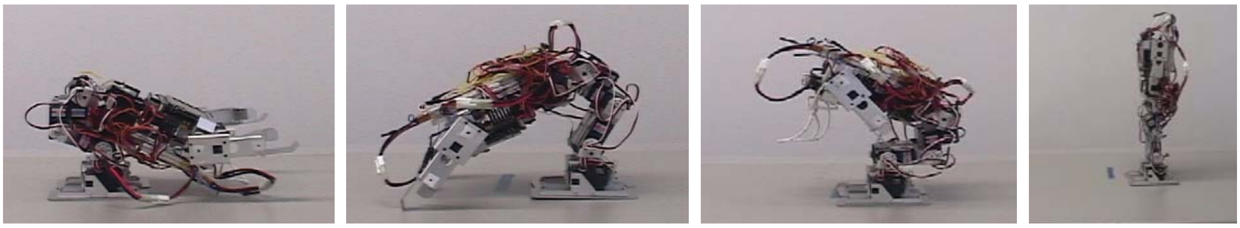
As seen earlier in **Fig. 21**, the maximum operating angle at short time settings became limited and operating speed was reduced, indicating that the legs cannot be raised as programmed. When video footage of walking and running at different time settings was analyzed, we found that although Genbe's legs are not raised sufficiently at short time settings, they slide forward due to forward leaning posture. Thus, even when legs are not raised sufficiently due to insufficient torque, stride length was maintained effectively at the same level so that forward speed remained proportional to pitch speed. Even when state (posture) data remained the same, Genbe was capable of walking and running over a wide speed range when only pitch speed was changed. Note, however, that to achieve such robust movement, we had to go through a trial-and-error process and acquire experience and "feeling" to determine state data (posture angles).

Figure 29 shows Genbe running at different speeds on ice- and snow-covered Lake Haruna using the same program as in **Fig. 24** [20]. Genbe's walking and running did not rely on contacting the ground or using friction and exert minimal load on joints. By employing state transitions that use the natural force of falling rather than contacting the ground, Genbe walks and runs robustly in a diverse range of environments, including floors of different buildings, hallways, interior rooms, and outdoors [21].

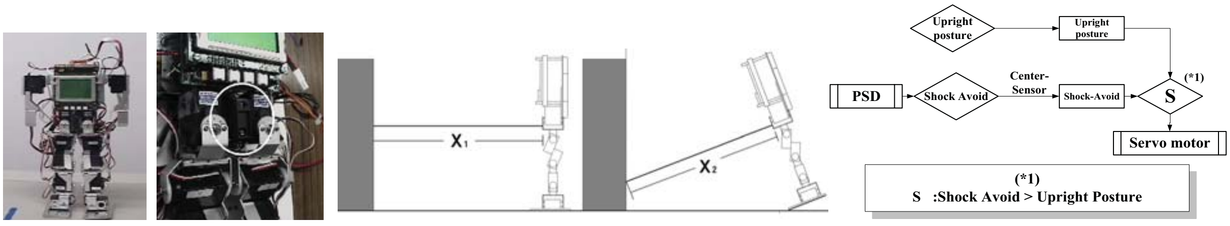
5. Adroit Movement Creation Based on State Transition and Excessive Drive Force Control

Figure 30 shows the states of the bipedal robot when pushed from behind when it senses falling, breaks the fall to minimize its impact, and recovers quickly thereafter. Using distributed control to move all robot joints and creating a state (posture) by controlling any excessive drive force hindering intended movement generate adroit movement as that shown in **Fig. 31**. The distance sensor (**Fig. 30(e)**) on the abdomen detects the time differential of the distance to the wall in front (**Fig. 30(f)**) to determine fall occurrence. The program uses subsumption architecture (**Fig. 30(g)**) [9].

Figure 32 shows time-series video images of a bipedal robot nanba walking as shown in **Figs. 22–24** in which it demonstrates quick response and robustness against sudden external disturbance (dynamic obstacles) based on subsumption architecture element behavior. When an obstacle appears suddenly in front, e.g., a person raises a hand to obstruct the robot's walking, the robot abruptly stops ($t = 0.40$ s), nanba-turns 90° to the right, and resumes walking ($t = 1.60$ s). Just as the robot attempts then to turn 90° to the left ($t = 3.00$ s), a dynamic obstacle suddenly appears to which the robot responds ($t = 3.20$ s) quite well, stopping 0.4 seconds after it recognizes the dynamic obstacle and assuming a standby enabling it to resume walking stably once the obstacle is removed. To

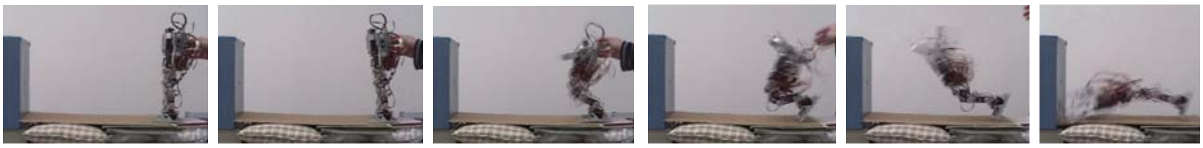


(a) State 1 (throwing the head back) (b) State 2 (crouching) (c) State 3 (rising) (d) State 4 (upright)



(e) (f) (g)

Fig. 30. Four biped robot states (a)–(d) for realizing autonomous impact avoidance during falling after being pushed from behind, and instantaneous recovery based on distributed body control. (g) Subsumption architecture.

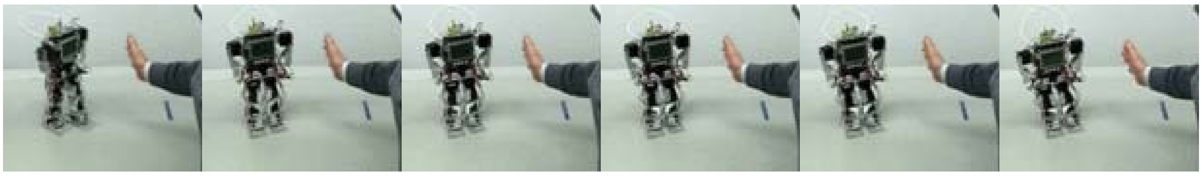


(a) t=0.68 s (b) t=1.12 s (c) t=1.24 s (d) t=1.36 s (e) t=1.52 s (f) t=1.64 s

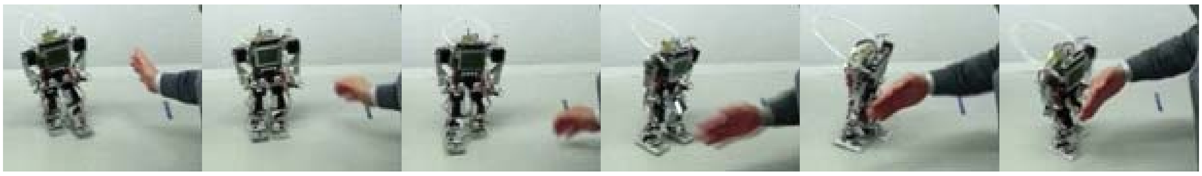
(g) t=1.76 s (h) t=1.88 s (i) t=1.96 s (j) t=3.04 s (k) t=3.20 s (l) t=3.72 s

Fig. 31. Simple autonomous impact avoidance during falling and instantaneous recovery of biped robot (Genbe No.5-2005) utilizing instability and taking only 2.5 seconds to recover.

t=0. 00s t=0. 20s t=0. 40s t=0. 60s t=0. 80s t=1. 00s



t=1. 20s t=1. 40s t=1. 60s t=1. 80s t=2. 00s t=2. 20s



t=2. 40s t=2. 60s t=2. 80s t=3. 00s t=3. 20s t=3. 40s

Fig. 32. Display of simple quick robust humanlike self-sustained stops of humanoid biped robot (Genbe No.5-2006) when presented with abrupt disturbance during nanba walking, stopping in 0.8 seconds (5 frames per 30).

make 90° or 180° directional changes to avoid the dynamic obstacle, the robot shifts its weight to the front (left) leg while leaning forward and extending the back (right) leg to the back, enabling it to turn without changing the position of the front leg.

6. Conclusions

We have proposed a method of generating adroit movement based on a constructive approach, presenting examples. Speed and robustness are implemented by instantaneously forming a state (posture) so that no blocks are created in the body and then transitioning from state to the next in one step.

Although robots with subsumption architecture as proposed by Rodney Brooks have often been misunderstood [22, 23], they have become better known to the public through the vacuum cleaner Roomba or PackBot, sent by iRobot Corporation of the United States to the site of the Fukushima Nuclear Power Station. Very few researchers in Japan are engaged in studying these robots, however, which may be one reason why Japanese robots have not been deployed at earthquake sites. The words of Italian philosopher Giambattista Vico – "verum esse ipsum factum," ("true itself is fact," "the true itself is made," or "the criterion and rule of the true is to have made it") [24] are fittingly applied to robots. In other words, it is how the robot moves and not empty words (systemization) that counts. Not knowing whether something works or not until it is put into action also applies to robots, which coexist with nature, living organisms, and people. We must go beyond Decartes' "Cogito ergo sum" ("I think, therefore I am") to the non-Cartesian approach of "Sum ergo cogito" ("I am, therefore I think") [25].

In conclusion, I dedicate this article to the memory of Dr. Kanako Miura of the National Institute of Advanced Industrial Science and Technology (AIST), who died in May 2013 in a traffic accident in Boston where she was working as a visiting research scholar. Just prior to her tragic death, she had displayed a keen interest in our research and proposed a joint study to realize dynamic movement based on inertia rather than muscle force, such as high jumping in track-and-field competition and jumps in figure skating. May she rest in peace.

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