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Synergistic 3D Limit Cycle Walking of an Anthropomorphic Biped Robot

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Abstract— **Human walking emerges from synergy of whole body dynamics: not only legs, but also a torso, arms, and a head are compliantly connected with each other by antagonistic muscles. Although change of activation of a muscle affects whole body motion, such synergy is supposed to play a great role for realizing stable walking. This paper investigates synergistic 3D limit cycle walking of an anthropomorphic biped robot whose joints are driven by artificial pneumatic muscles antagonistically. Since its walking emerges from the synergy, we cannot design the desired trajectory in a top-down manner, but can change an activation pattern of the muscles and figure out appropriate parameters for stable walking. We experimentally demonstrate that the biped walks stably with a simple limit cycle controller. This is the pioneering work for investigating synergistic stable walking of a whole body humanoid.**

I. INTRODUCTION

We humans have complicated body dynamics: body parts are connected by many compliant antagonistic muscles, which provides compliance and redundancy. Therefore, it is difficult to specify the precise motion of our arms and legs independently, but behavior emerges from synergy of whole body dynamics including such compliance and redundancy [1]. Synergistic behavior production is supposed to play a great role for adaptability and stability of human behavior [2].

There have been several attempts to understand human walking from the viewpoint of synergy by constructing a dynamical simulator in the field of bio-mechanics [3, 4]. Some of them took not only the dynamics of the body parts, but also characteristic of muscles and even that of neural circuits into account. Through these attempts, mechanism of human walking was gradually revealed to some extent. However, they only observed behavior of the simulated agent and did not try to figure out a design principle. Therefore, the observation was not utilized for designing a real biped walking robot.

Meanwhile, many trials have been made to reproduce biped walking by real biped robots/humanoids. Roughly speaking, there are two kinds of approaches to realize biped walking: a ZMP-based approach and a "passive dynamic walking" based approach. In the ZMP-based approach, they mainly adopted electrical motors and reduction gears to achieve trajectory tracking whose trajectory was calculated based on the ZMP analysis [e.g. 5, 6, 7]. The electrical motors and reduction gears play a great role to achieve high-performance trajectory tracking, but on the other hand, it is relatively difficult to realize joint compliance by utilizing them. Since the impact with the terrain is not fully predicted because it is not perfectly flat, on-line calculation of the desired trajectory may not be in time and computationally very expensive. Therefore, the resultant walking tends to be brittle against terrain change.

"Passive dynamic walking" is an alternative approach to natural walking [8], and was also studied intensively [9, 10, 11]. Several walking robots have been developed that utilize such passive dynamics for energy efficient walking [12-15]. However, these robots did not take the compliance of the joints into account. To study contribution of the body synergy for stabilizing walking, some mechanism is required for providing compliance. Takuma and Hosoda [16] developed a 2D biped robot driven by antagonistic artificial muscles that could realize certain compliance in the joints and investigated its limit cycle walking. However, the robot did not have a torso, and its motion was restricted within a 2D plane.

In this paper, we investigate synergistic 3D walking of an anthropomorphic biped walker. Since all the joints of the humanoid are driven by artificial pneumatic muscles antagonistically, we can study on the synergistic whole body behavior. The dynamics of the whole body is so complicated that it is almost impossible to design the "desired trajectory" in a top-down manner. To realize stable walking, we design an activation pattern of the artificial muscles: a simple limit cycle controller. There have been several whole body humanoids whose joints are driven by tendons and/or compliant actuators so that we can study on synergistic behavior [17, 18], but the robot, "Pneumat-BT", described in this paper is the only one that can walk dynamically utilizing synergy of the whole body dynamics. This is the pioneering work for investigating synergistic stable walking of whole body humanoid.

This paper is organized as follows: First, we describe a new design of an anthropomorphic biped walker whose joints are driven by pneumatic muscles antagonistically. Then, a limit cycle controller is introduced to realize dynamic walking. Since the whole body dynamics is too complicated to design its precise motion, we instead design excitation of the muscles so that we can obtain stable walking behavior by experimental trials. Several experimental results demonstrate that the limit cycle controller can realize 3D stable walking on flat terrain.

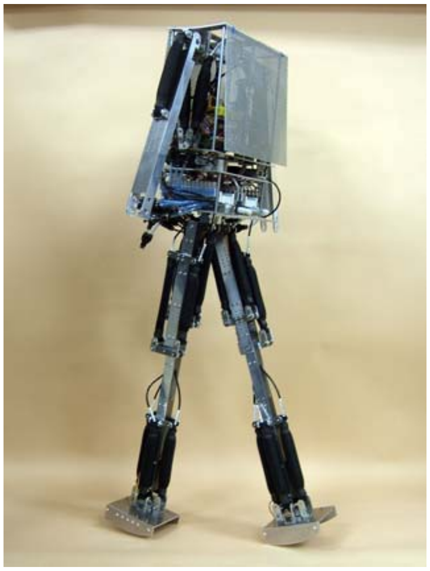

Figure 1: An anthropomorphic biped walker “Pneumat-BT”. It has 13 degrees of freedom and 26 McKibben artificial muscles.

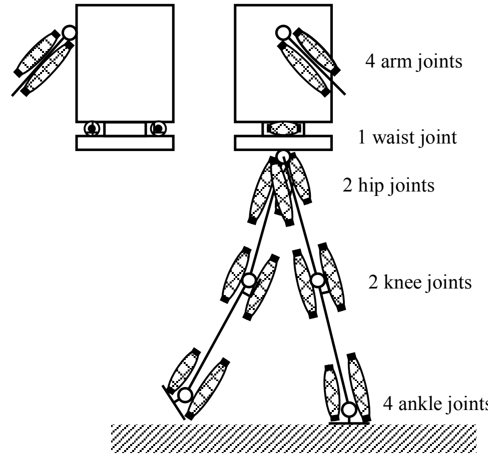

Figure 2: A sketch to describe how the joints are driven by pairs of pneumatic artificial muscles. Each arm has 2 DOFs. The robot has 1 DOF waist joint to twist, 2 hip joints each of which drive one leg. Each leg has a 1 ODF knee and a 2 DOF ankle.

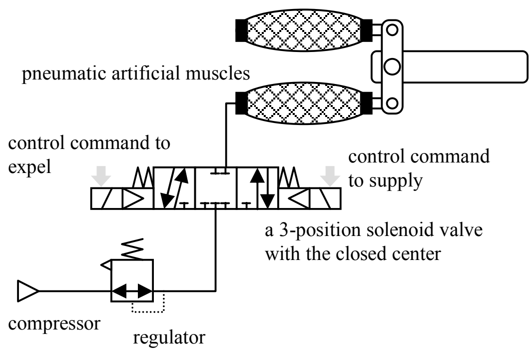

Figure 3: A pneumatic control architecture. We adopted 3-postion solenoid valves with the closed center so that the valve can be closed when it is not actively controlled.

II. AN ANTHROPOMORPHIC BIPED WALER “PNEUMAT-BT”

A. *Body structure and placement of muscles*

Figure 1 shows the anthropomorphic biped walker named “Pneumat-BT (Biped, Twister)”. Its height, width, leg length, length of the thigh, and that of the shank are 112[cm], 32[cm], 70[cm], 28[cm], and 48[cm], respectively. The robot is designed to be self-contained: it has all air valves, control boards, and a battery on the body. We can put CO_2 cartridges for supplying air, but is not actually used for the experiments in this paper because of the running cost. Instead, a compressor is used to supply 1[MPa] compressed air to the regulator. The pressure to the air valves is regulated in either 0.5[MPa] or 0.65[MPa]. The robot weights approx. 9.6[kg] excluding the cartridges. The robot has 13 degrees of freedom each of which is driven by an antagonistic pair of pneumatic actuators. We adopt McKibben pneumatic artificial muscles to drive the joints [19, 20].

In Figure 2, we show a sketch to describe how the joints are driven by pairs of pneumatic artificial muscles. It has two arms each of which has 2-DOF, 1-DOF waist joint to twist, 2 hip joints each of which drives one leg. Each leg has a 1-DOF knee and a 2-DOF ankle.

The robot has round soles so that we can adopt the existing control technique for bipeds based on passive dynamics [14, 15, 16]. Walking is, therefore, realized relatively easy by adopting the existing technique, while the robot cannot stand still.

B. *Pneumatic control architecture*

Figure 3 shows the flow of air: pneumatic control architecture. The compressed air ($\cong$ 1[MPa]) is supplied from the compressor to the regulator. The air is, then, fed into a 3-position solenoid valve with a closed center position that is controlled by the on-board computer. The muscle is supplied and expelled according to the computer command.

We adopted 3-position valves that allow the robot realizing spring-like property of joints by just closing the valves of the antagonistic muscles. It can also change the stiffness of joints by regulating amount of the air inside.

C. *Electric and information flows*

Figure 4 describes the electric and information flow. The robot has a touch sensor on each foot. The on/off information is fed to a 16-bit single chip microcomputer H8-3069 (clock: 25MHz, produced by Renesas Technology Co.). According

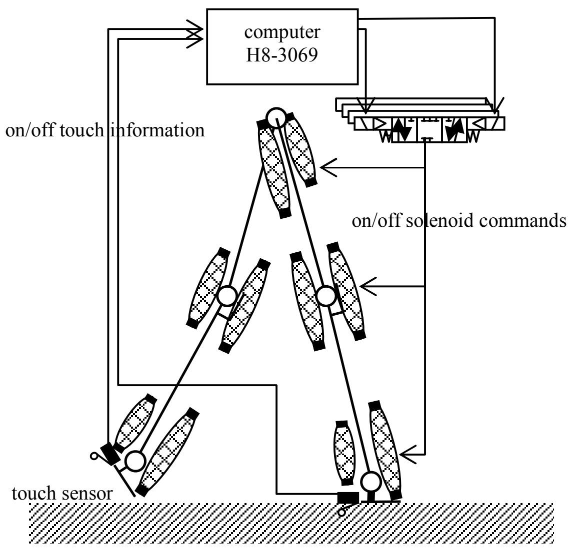

Figure 4: Electric and information flow. The touch information obtained by the sensor is fed to a board computer H8-3069. The control commands are calculated, and the on/off command is fed to the solenoids.

to the received information, the computer outputs open/close commands to the solenoid valves through amplifiers.

III. A LIMIT CYCLE WALKING CONTOLLER

In this paper, we adopt a simple feedforward-type controller for limit cycles, almost the same one used in [16]. The effectiveness of the controller is proved for a biped without torso within 2D, but not yet known whether it is effective for an anthropomorphic biped walker with a torso. Moreover, we also have to take the frontal and horizontal balance into account since the robot walks in 3D.

There is time delay between the inner pressure of the muscle and operation of the valve (shown in Figure 5). We conducted a preliminary experiment to supply and expel 0.6[MPa] air to and from an unloaded McKibben pneumatic actuator whose length was 0.15[m]. We used a compact on/off valve with a maximum flow rate of 313.2 [l/min]. We found that the time delay exceeds 0.4[s], which is considerably large. We also conducted experiments at other pressures, but the delay was almost the same. We can utilize such delay for changing the compliance of the actuator by regulating the opening duration of the supplying/expelling valves.

Waist (left and right), hip (front), and knee (front) muscles are controlled based on the touch information from the sensors on the soles (see Figure 6). Fixed valve operation is initiated by the touch information. The parameters T_E, T_S, and T_K determine the time how long the robot swings a leg, tension of the hip of the stance leg, and the time how long the swing knee bends, respectively. The procedure is:

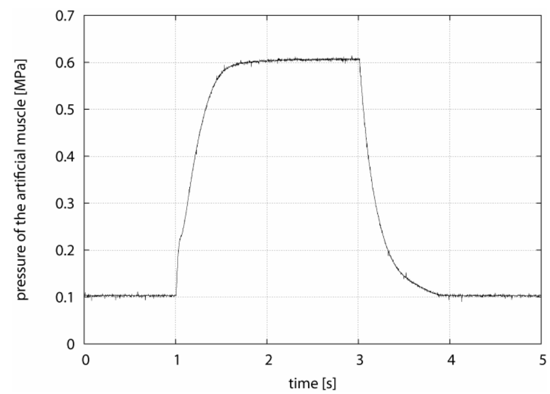

Figure 5: There is time delay between the inner pressure of the actuator and operation of the valve. In this preliminary experiment, the actuator is unloaded. The supplying valve is open at 1[s], and the expelling valve is open at 3[s]. We can see more than 0.4[s] delays.

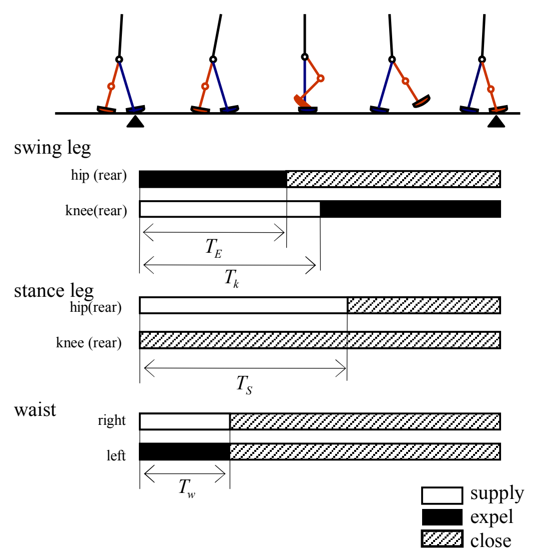

Figure 6: a ballistic walking controller for limit cycles. The valve operation procedure is triggered by the heel strike information.

(i) Just after a touch, air is expelled from the hip (rear) muscle of the swing leg until T_E while air is supplied to the hip (rear) muscle of the stance leg until T_S. This operation generates the propulsion force and at the same time, determines the tension of the hip.

(ii) Meanwhile, air is supplied to the knee (rear) muscle of the swing leg until T_K so that the knee bends slightly and the swing leg can clear the ground. Then, air is expelled from the muscle to let the knee straight again.

(iii) Just after a touch, the waist is also driven by the muscles.

If T_W is positive, the right muscle contracts and the light one relaxes when the right leg swings.

Other muscles are supplied with fixed amount of air before a walking trial, and the valves concerned are all closed during walking. This amount determines tension, and therefore, strongly affects the walking stability. This is the synergistic effect of the whole body and investigated in detail in the next section.

IV. EXPERIMENTS

We now have 4 control parameters and 10 parameters for statically filled pneumatic muscles (In Table 1, muscles painted in white are statically filled ones). As already discussed, walking behavior of the robot emerges from the synergistic body dynamics. Therefore, even if we change just one parameter, the whole behavior of the robot will change. This fact makes searching the appropriate parameters extremely difficult. To reduce searching effort for appropriate parameters, (1) we stiffened the arms supplying the muscles with air adequately (we supplied air for 2[s]) since we liked to simplify the stability analysis; (2) we also stiffened the pitching direction of the ankles since the robot had round soles which enabled the robot lean forward even without ankle compliance; and (3) we supposed that we could categorize the parameters into three groups: mainly contributing to sagittal, frontal, and horizontal movement. Accordingly, we first tuned the parameters which concerned the motion in the sagittal plane. Other parameters were determined arbitrary. Once we could make the robot walk with a set of parameters, we proceeded to investigate other parameters concerned to the motion in the frontal and horizontal planes subsequently. It is obvious that the motion in a plane is strongly coupled with other motion. But, we assumed that we could find appropriate parameters by repeating these searches.

The terrain used for these experiments is a flat carpet (shown in Figure 7) and a flat rubbery athletic track.

A. *Tuning parameters for sagittal movement*

First, we tuned parameters related to the motion in the sagittal plane. Tuned parameters were T_E, T_S, T_K, and fixed duration for supplying air to muscles. In these experiments, the ankles were fixed by metal bars so that the angle was 85 degrees. The waist joint was strained by fully supplying the air to both muscles.

The front muscle of the knee were supplied with air for 800 [ms] so that the joint could be bent smoothly when the rear one was supplied with air. This parameter is not so important for stable walking, but for the clearance of the leg. The supply duration for the hip front muscle concerns how large the upper body leans forward. By trial and error, we found 400[ms] was the appropriate duration to realize a good upper body attitude. The used parameters are summarized in Table 1.

Figure 7: Experimental setup: the anthropomorphic biped robot "Pneumat-BT" walks on a flat carpet.

Table 1: Initial supply duration for the pneumatic muscles ([ms]). The muscles in gray are controlled on-line so that their pressure changes according to time.

Muscles		initial supply duration
hip	front	400
	rear	(600)
knee	front	800
	rear	(0)
ankle	front	2000
	rear	2000
	inside	(physically fixed)
	outside	(physically fixed)
arm	front	2000
	rear	2000
	inside	2000
	outside	2000
waist	right/left	2000

By using this set of duration, we obtained appropriate control parameters T_E =320[ms] and T_K =400[ms] by trial and error. T_S is set to be equal to the walking period. Observed walking motion in the sagittal plane captured by a motion capture system is shown in Figure 8. Walking cycle and step length are approximately 0.7 [s] and 0.35 [m], respectively.

B. *Tuning parameters for frontal movement*

If the robot motion is constrained within 2D (e.g. [16]), we only have to deal with the parameters for walking stability in the sagittal plane. However, if the robot moves in 3D, then we should take not only the walking stability but also the frontal

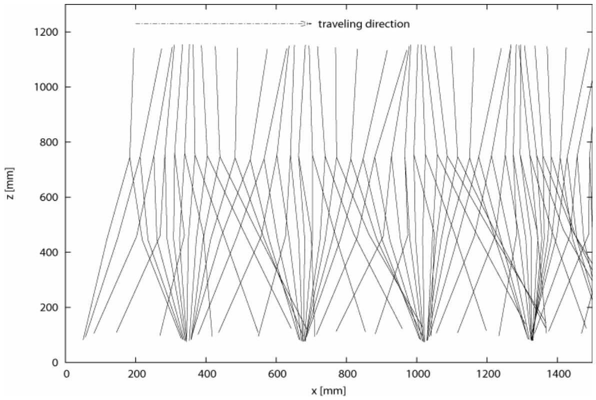

Figure 8: Observed walking behavior captured in the sagittal plane in every 1/12 [s]. The biped walks rightward stably.

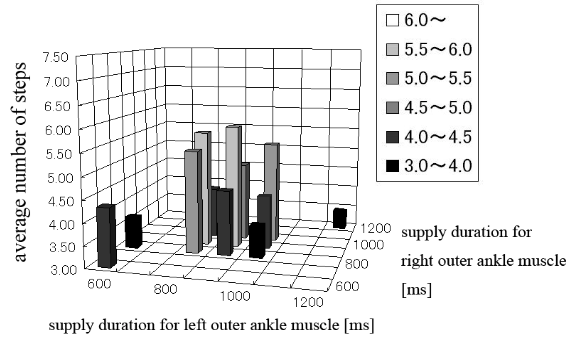

Figure 9: Average number of steps with respect to the supply duration for ankle muscles when the supply air pressure was 0.5 [MPa]. When supply duration is around 900 [ms], the biped can walk 5 to 6 steps in average.

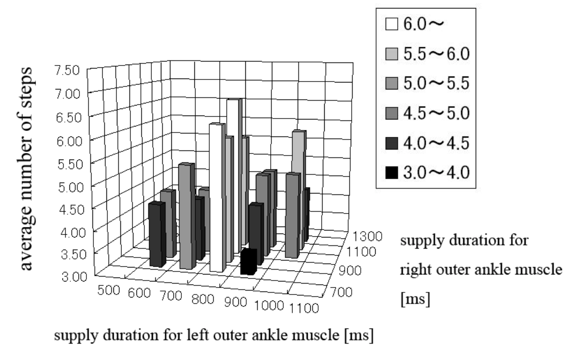

Figure 10: Average number of steps with respect to the supply duration for ankle muscles when the supply air pressure was 0.65 [MPa]. When supply duration is around 900 [ms], the biped can walk more than 6 steps in average.

and horizontal balance into account. For the frontal balance, inside and outside muscles of the arms, and those of the ankles play important roles. In this paper, for simplicity, the arms are stiffened by supplying air to the muscles adequately. Therefore, we investigate to what extent the ankles contribute to the frontal swinging stability. We investigated walking behavior in different supply air pressure: 0.5MPa and 0.65MPa. The inner muscle is supplied with air for 4 [s], which makes it fully contract. Figure 9 and 10 show the relation between the supply duration to the outer muscles (left and right, since the real robot is not manufactured completely symmetric) and the average number of walking steps. There seems to be an appropriate ankle angle for stable walking: the angle should not be too small and not too large. We can also observe that the stiffer the ankle is, the more the number of steps becomes. This result may lead to a simple conclusion: the more stiff the ankle is the more stable walking becomes. We could not conduct more experiments with higher pressure because of the upper pressure limitation of the muscles.

However, note that these experiments are conducted only on a flat plane. The compliance seems effective when the terrain is rough, which we should conduct more experiments.

C. *Tuning parameters for horizontal movement*

The effectiveness of the waist movement is investigated as well: horizontal movement. The muscles of the waist joint are controlled by changing T_W. Figure 11 and 12 show the average numbers of steps when the waist is controlled. We conducted experiments on two kinds of terrain: a carpet (Figure 11) and a rubbery sheet used for an athletic track (Figure 12). It was relatively difficult to estimate the physical parameters of the terrain, but qualitatively, the carpet is more compliant and has more friction than the rubbery sheet. As far as the robot walks on the carpet, anti-phase motion, that is, when the left leg is moving forward, the right arm is moving forward, seems appropriate. On the rubbery sheet, on the other hand, too strong anti-phase movement is not suitable for walking. These results depend on the compliance and friction of the terrain, but it is difficult to lead to quantitative conclusion here.

V. CONCLUSION AND FUTURE WORK

In this paper, we have investigated synergistic 3D walking of an anthropomorphic biped walker. We have shown several experimental results how a parameter affects whole body motion. By tuning the parameters, we could make the biped walk more than 22 steps at most.

As we discussed in the introduction, it is reported that the compliance contributes a lot to the stability of walking, but from the obtained results, we could not lead to the same conclusion. We have to conduct more experiments on rough terrain to show this. Moreover, there are so many points to be studied in the future on the platform. Some of them are:

(i) We should study on the effect of preflex [21,22]. The pneumatic artificial muscle has large time-delay [23] and so does a natural muscle. One of key ideas to deal with the delay is preflex. In this paper, we studied about the stiffness of the ankle, but were not enough to conclude

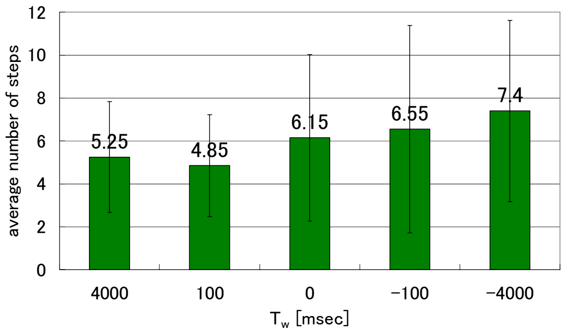

Figure 11: Average number of steps with respect to waist motion control on a carpet. When the robot walks on the carpet, anti-phase motion seems appropriate.

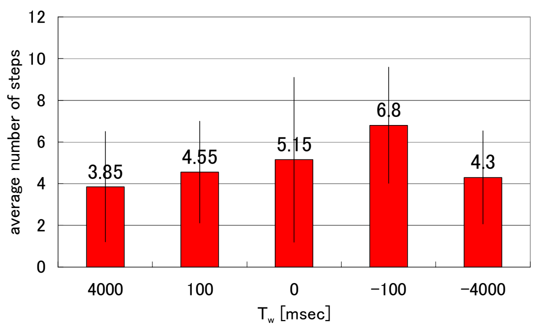

Figure 12: Average number of steps with respect to waist motion control on a rubbery sheet. When the robot walks on the sheet, too strong anti-phase movement is not appropriate.

the results.

(ii) We should investigate on the shape of the sole. The round sole is convenient to realize passive dynamic walking, and therefore, we adopted it for the platform. However, it is obvious that the robot cannot stand still with such round soles. We should study that even with a flat sole; the robot can walk making use of the proposed feedforward control method. This issue strongly relates to the first point since there is possibility to "emulate" the round sole by appropriate compliance [24].

(iii) We should derive a controller for arms. It is obvious that we can utilize them to maintain the balance of the biped. Again, the response of the pneumatic muscles is very slow; they should also be controlled in a feedforward manner.

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