H. Ahmad, Y. Nakata, Y. Nakamura and H. Ishiguro, "A Bipedal Robot with an Energy Transfer Mechanism between Legs: A Pilot Study," 2018 IEEE International Conference on Robotics and Biomimetics (ROBIO), Kuala Lumpur, Malaysia, 2018, pp. 1256-1261, doi: 10.1109/ROBIO.2018.8664868.

A Bipedal Robot with an Energy Transfer Mechanism between Legs: A Pilot Study

Huthaifa Ahmad[1], Yoshihiro Nakata[1], Yutaka Nakamura[1] and Hiroshi Ishiguro[1]

Abstract— **Humans' adaptability to overcome the continuous changes of the environment is a result of their bodies' ability to change the way it interacts with the given situation. Therefore, augmenting robots with adaptable behavior, requires to exploit the possible dynamics emerging from the different interactions among all parts of their bodies. From this perspective, here in this pilot study, we developed a simple structure bipedal robot that enables a mutual interaction between its legs through an actuator network system (ANS). With this mechanism, the robot was enabled to transfer energy between its legs during locomotion. And as the experimental results showed, in terms of the roll motion and the vertical oscillation of the robot's body, the robot was able to produce a more stable locomotion behavior with mutually connected legs compared to other types of independent legs that do not have the ability to interact with each other.**

I. INTRODUCTION

The natural walking behavior of humans results from the interaction among all the parts of the body. And it is not only restricted on the dynamics of each leg separately; rather the synergy between the two legs and the way they interact with each other, along with the other parts of the body plays a significant role in the adaptive walking behavior of humans [1]. Due to these complex interactions among all the parts of the body, it is not an easy task to realize bipedal robots that are able to walk like humans. Therefore, for many years now, building bipedal robots with walking behavior similar to that of humans has become a subject undergoing intense study in the robotics field [2],[3],[4]. Two approaches have been followed for realizing such robots, the numerical computation approach (classical), and the embodied intelligence approach (modern).

Robots like HRP-2 [5] and Honda's ASIMO [6], are examples of bipedal robots following the classical approach. These robots showed an impressive array of abilities that made them classified among the most advanced humanoid robots. However, these robots require a precise model of the surrounding environment, and demand extra computational duties for calculating the trajectories of their body's joints to realize adaptability.

To obtain robots with natural and more efficient walking patterns, researchers following the embodied intelligence approach on the other hand [7], have developed robots able to exploit its dynamics and the material properties (e.g., elasticity/ stiffness) of their bodies. Many of these robots were developed based on bio-inspired models [8],[9]. Passive Dynamic Walkers (PDWs) are examples of bipedal robots following this approach [10],[3],[11]. Without any actuator or control strategy, PDWs have demonstrated natural, and more efficient humanlike walking behavior; mainly by focusing on utilizing the inherent dynamics of the swinging limbs and gravity. However, the ecological niche (i.e., the environment in which the robot is capable of operating) is extremely narrow; as these robots are only capable of walking down inclines of certain angles. Therefore, these robots lack adaptability, and cannot cope with other different terrains.

To augment a robot with adaptable capabilities, it has to change its hardware dynamics accordingly to overcome the continuous changes in the environment. Therefore, recent studies have considered the use of actuators with variable elasticity, to adapt the robot's morphology to the desired task and environment [12],[13],[14]. Bipedal robots with compliant limbs have shown a variety of stable and efficient motions [15],[16],[17],[18]. However, without exploiting the different dynamics emerging from the direct interactions among all parts of the robot's body, it might not be enough to generate a variety of locomotion patterns to cope with the various situations.

Here in this research, to realize whole-body dynamics, and to ensure a direct mutual interaction between the robot's limbs, we use an Actuator Network System (ANS). ANS was introduced in recent researches to improve a robot's adaptability during locomotion with the surrounding environment [19],[20]. The robot had a swinging mass with a rotary motor attached to its body, which provides energy into the whole system for locomotion. Its ANS composed of multiple cylinders that are connected by many valves, and passive, fluid-mediated interactions between them are used to change the robot's hardware dynamics.

This paper describes the usage of ANS in developing a simple structure bipedal robot based on Klann mechanism, shown in figure 1. The robot uses an ANS to transfer energy between its legs through the passive interaction between the pneumatic cylinders mounted on its legs. By focusing on the role of energy transfer between the robot's legs, this study aimed to investigate the effect of different connection patterns on the robot's stability.

The rest of the paper is organized as follows. In Section II, we introduce the developed bipedal robot and show its design in details. We also explain the valve system of the implemented ANS and its different connection patterns. Section III, presents the conducted experiments, its settings, and show its results. In Section IV, we provide some discussions

[1] Huthaifa Ahmad, Yoshihiro Nakata, Yutaka Nakamura, and Hiroshi Ishiguro are with Department of Systems Innovation, Graduate School of Engineering Science, Osaka University, 1-3 Machikaneyama, Toyonaka, Osaka 560-8531, Japan. {huthaifa.ahmad, nakata, nakamura, ishiguro}@irl.sys.es.osaka-u.ac.jp

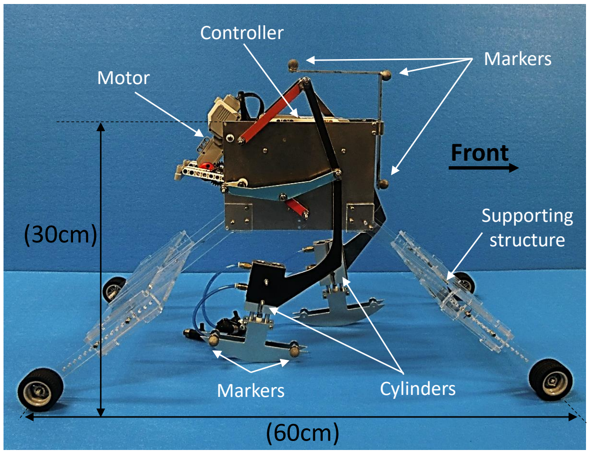

Fig. 1. Bipedal robot with ANS.

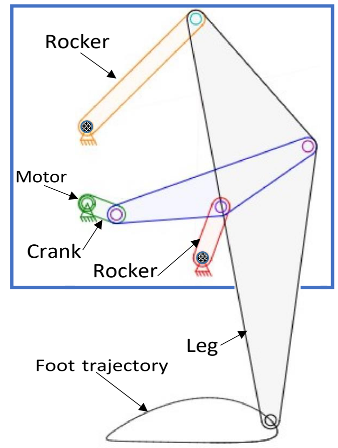

Fig. 2. Diagram of Klann linkage.

on the results and evaluate the stability of the robot in terms of the roll motion, and vertical oscillation of the robot's body. This section also points to some areas of research for future work. Section V concludes the paper.

II. Bipedal robot with actuator network system

A. Structure of the Robot

With a pneumatic cylinder attached to each leg of the proposed bipedal robot, the compliance of each leg in addition to the energy transfer between them become adjustable. The 30 cm height robot is built with a simple structure based on Klann linkage (figure 2) that is mechanically coordinated by a single-degree-of-freedom [21]. The robot consists of a servomotor (LEGO MINDSTORMS EV3 large servomotor) responsible for the robot's locomotion, two identical Klan linkages coupled together at the crank and one-half cycle out of phase with each other are representing the robot's legs, allowing the robot's body to travel parallel to the ground. Each of the linkages consists of the robot's body frame, a crank, two grounded rockers, and two couplers all connected by pivot joints. A supporting structure is also added to the robot to ensure stability and to prevent the robot from falling down. The length of the supporting structure is set in a way that all of its four wheels are touching the ground when the robot is in its initial posture as shown in figure 5-c.

B. Connection Patterns

As mentioned earlier, Actuator Network System (ANS) was proposed in recent researches to improve a robot's adaptability during locomotion [19],[20]. The essence of ANS is the mutual interaction among a network of interconnected actuators. Whereas with every pattern connecting these actuators, different body dynamics will emerge.

A simple valve system of two hand-valves forms the ANS of our bipedal robot. It connects the robot's legs as shown in figure 3. Valve (a) links the advancing chambers (proximal) of the two cylinders together, while valve (b) links the retracting chambers (distal) together. By opening/closing the valve system with various combinations, different interactions between the actuators will emerge to generate a variety of dynamics for the robot's body.

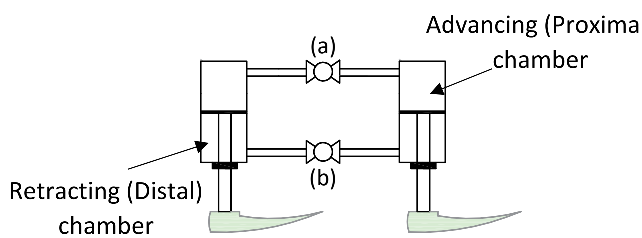

Fig. 3. The valve system of the ANS.

During the conducted experiments, the robot's movement was examined with three different types of legs as illustrated in figure 4. Under type 1, both of the hand-valves are kept open to allow energy transfer between the two legs. For example, once the robot steps on its right leg, the piston of the cylinder attached to this leg will fully retract. In response to that, the left leg will fully expand due to the air transmission between the two legs. Under type 2, both of the valves are kept closed as illustrated in figure 4-b, to prevent the direct interaction between the robot's legs. In this case, the robot has compliant legs; its legs are attached to air springs created by the locked air inside the chambers of each actuator. As shown in figure 4-c, under type 3, the robot has stiff legs, since the pistons of both cylinders are locked-up at their half-advanced lengths.

III. Experiments

A. Procedure and Experimental Settings

To examine the effect of the three different types of legs (mentioned in Section II) on the stable walking behavior of the robot, both of the roll motion (shown in figure 5-a), and the vertical oscillation of the robot's body (shown in figure 5-b) were observed and measured during the conducted experiments.

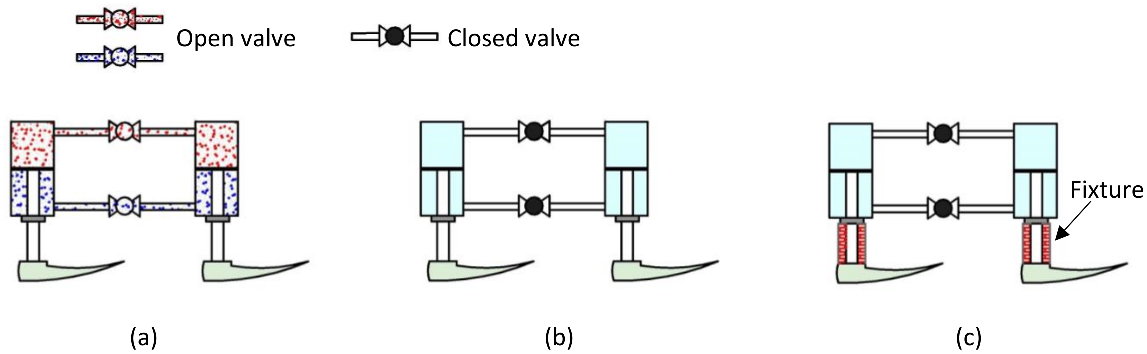

Fig. 4. Applied connection patterns during the experiments. (a) Type 1: Mutually interconnected legs, (b) Type 2: Compliant independent legs, and (c) Type 3: Rigid legs.

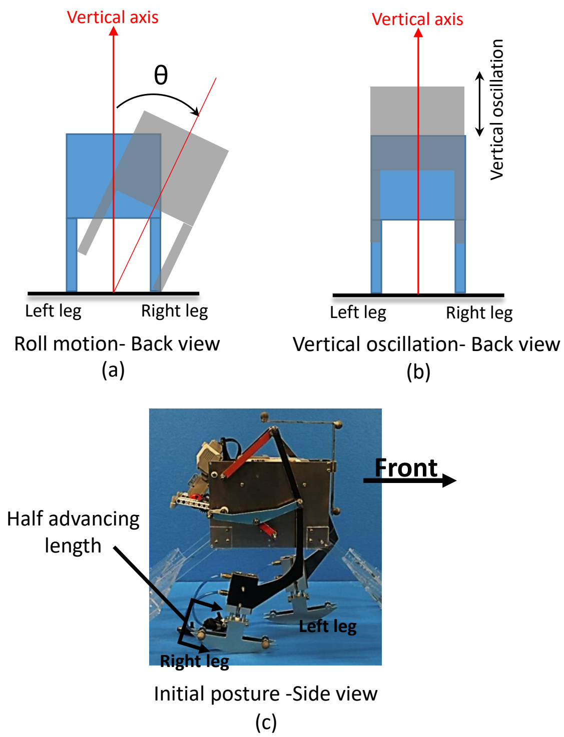

Fig. 5. (a) Demonstration of the roll motion, (b) Demonstration of the vertical oscillation of the robot's body, and (c) The initial posture of the robot: both of its legs are at their half-advanced lengths. The left leg is in the front, and the right one is in the back.

The steps below are the performed preparation procedures before starting any trial:

- Pumping air into the ANS using an air compressor.
- Setting the air pressure inside the cylinders with proper values to get the legs at their half-advanced lengths.
- Selecting one of the three previously mentioned connections by manually open/ close the valves respectively, and fixing it during the robot's locomotion.

After that, we start the experiment with the robot having the same posture for all trials. Its right leg is in the back while the left one is in the front as shown in figure 5-c. For each connection, three trials were conducted. The motion of the robot was analyzed by placing reflective markers on the robot as shown in figure 1. To track those markers, a motion tracking system (OptiTrack-V120:TRIO) was used.

B. Results

For the three trials conducted for each connection, the roll motion in addition to the vertical oscillation of the robot's body during locomotion are graphed in figures 6-a and b. As can be inferred from the graphs, With connected legs to allow energy transfer between them, the robot realizes the lowest oscillation amplitude of both the roll motion and the vertical oscillation of the robot's body, with ranges of (2.06°), and (4.32 mm) respectively. On the other hand, the robot with rigid legs had the shakiest behavior with oscillation amplitude ranges within (7.34°) for the roll motion, and within (10.27 mm) for the vertical oscillation of the robot's body. The robot with compliant legs (type 2) has amplitude values that lie between the other two types of legs, closer to type 3. Based on the applied t-test with 4 degrees of freedom, the experimental results showed a significant difference ($p <= 0.001$) in behavior between the three connections, as shown in figure 7. Table I summarizes the results of the conducted experiments. It compares the average of both, the roll motion and the vertical oscillation of the robot's body for the three types of legs.

TABLE I

AVERAGE RANGE OF BOTH THE ROLL MOTION'S ANGLE [DEG] ± S.D, AND THE VERTICAL OSCILLATION [MM] ± S.D.

	Range of the roll motion [deg]	**Range of the vertical oscillation [mm]**
Type 1	2.06 ± 0.18	4.32 ± 0.34
Type 2	5.47 ± 0.11	8.92 ± 0.11
Type 3	7.34 ± 0.45	10.27 ± 0.16

The snapshots of figure 8 display one of the three conducted trials for each type of legs. It shows the bipedal robot during the first gait cycle of its locomotion.

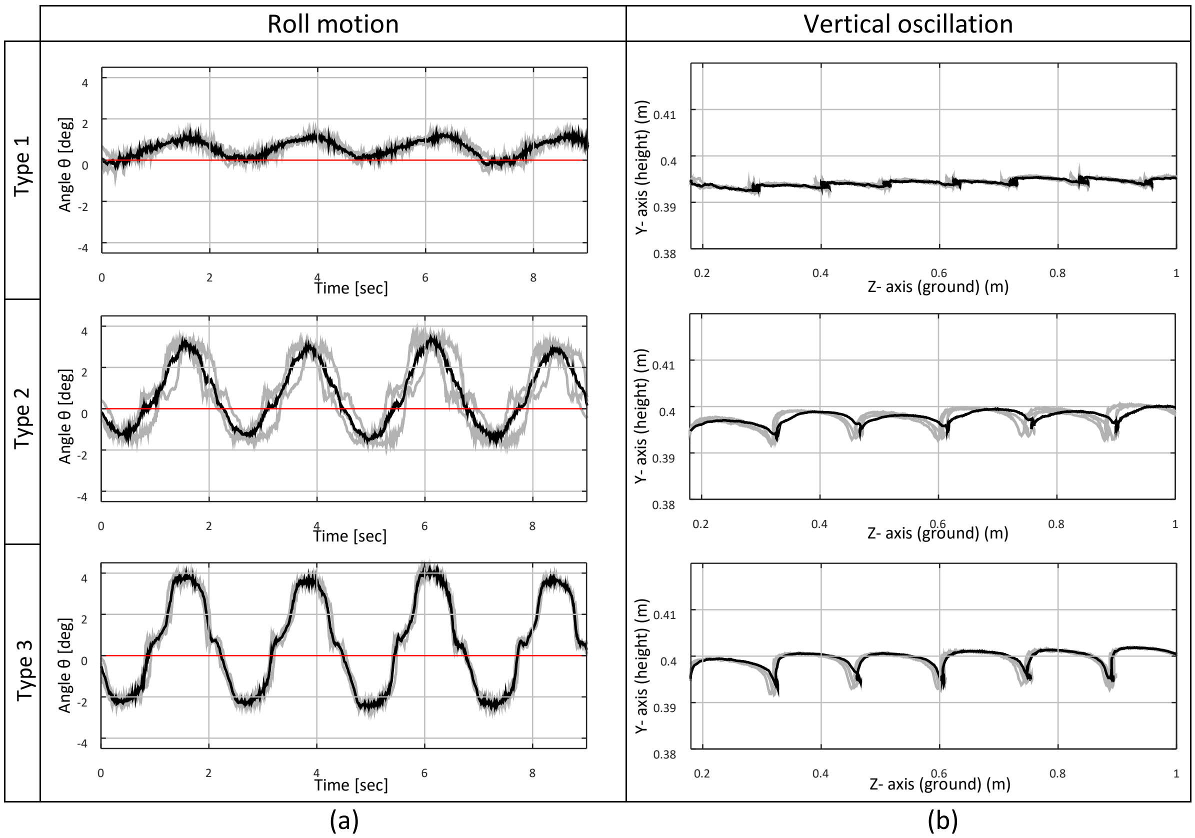

Fig. 6. Comparison of (a) the roll motion and (b) the vertical oscillation of the robot's body under the three types of legs. The black lines represent the average behavior among the three conducted trials of each type, which are drawn in gray colors. The horizontal red lines (Θ = 0°) of the roll motion graphs, represents the vertical axis shown in figure 5-a.

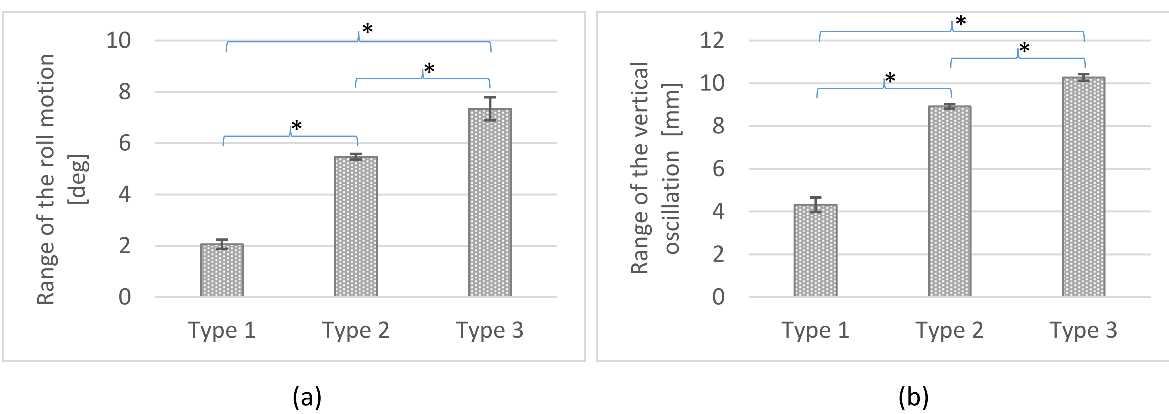

Fig. 7. (a) Average range of the roll motion's angle [deg] $\pm$ S.D. (b) Average range of the vertical oscillation [mm] $\pm$ S.D. * indicates $p <= 0.001$.

IV. Discussion

As the experimental results showed, by changing the interaction between the actuators of the ANS, the robot's walking behavior was also changed even though all of the other experimental settings remained the same. Whereas can be inferred from the conducted experiments with three types of connections, the robot showed a noticeable difference in behaviors regarding the vertical oscillation of the robot's body and the roll motion. These differences in behaviors could be exploited to enhance the robot's adaptability based on the given situation.

During the robot's locomotion with mutually interconnected legs (which allows energy transfer between them), the robot was able to move in a smoother and more stable way compared to the other two connections of the rigid and compliant legs. It showed low oscillation amplitudes of both the roll motion and the vertical oscillation of the

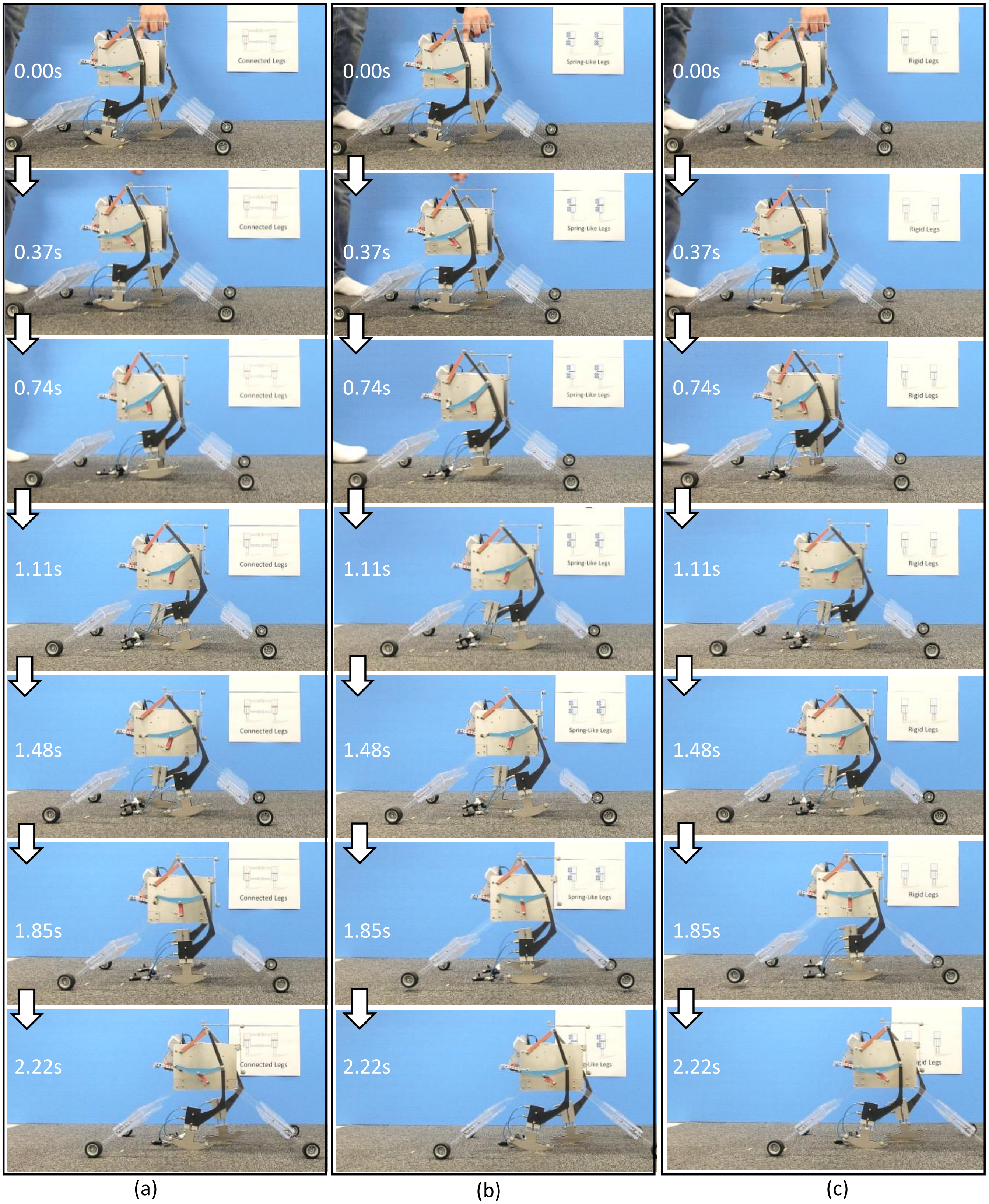

Fig. 8. Time-series photographs of one gait cycle of the bipedal robot during locomotion, showing one of the conducted trials of each connection pattern. (a) Type 1, (b) Type 2, and (c) Type 3. The interval between every two successive pictures is 0.37 s.

robot's body. However, the experiments here were conducted to test the robot's behavior on one type of ground materials (carpet on a leveled ground). Therefore, these results might get changed on other ground materials with different texture and different inclinations. And there, different connection patterns might be required to realize better performance.

Although the obtained promising results show possible improvements on the robot's walking behavior by applying ANS, our robot (introduced in this paper) is just a prototype that has some drawbacks and limitations that need to be addressed in the future. For example, the robot's demands to an extra supporting structure to keep it in balance and preventing it from falling down during locomotion, affects the robot's gravitational reaction force. Another thing, the robot was more leaning to the right side during locomotion compared to the left side, which indicates the asymmetrical distribution of the robot's mass. Therefore, in the future, improving the design of the robot would be the first thing to be done, to realize a self-balanced bipedal robot.

In this paper, the experiments were conducted to investigate the improvements that can be realized by utilizing ANS. However, the experiments were only done on one type of ground materials, and with only three types of legs. Thus, in the future work, and after upgrading the robot's design, the robot's performance with different connection patterns will be examined on different ground materials with different inclinations. The effect of different types of independent legs with adjustable elasticity will also be considered. In addition to that, we will look for other emerged differences in behaviors that might occur by changing the way the robot's legs interact with each other. For example, the pitch and roll motions, walking speed, the period of swing phase, stance phase and double limb support during the gait cycle, and how the robot will adapt to the variations of loads weights.

V. CONCLUSIONS

Here in this research, we introduced the development of a bipedal robot prototype. The robot uses an ANS to transfer energy between its legs through the passive interaction between the pneumatic cylinders mounted on its legs. By focusing on the role of energy transfer between the robot's legs, this study aimed to investigate the effect of different connection patterns on the robot's stability. To examine the effect of the three different types of legs on the stable walking behavior of the robot, both of the roll motion, and the vertical oscillation of the robot's body were examined during the conducted experiments. As the results showed, having direct interaction with the ability to transfer energy from one leg to the other, the robot was able to move smoother with stable behavior as it realizes low oscillation amplitude of both the roll motion and the vertical oscillation of the robot's body. The robot with rigid legs, by contrast, had the highest oscillation amplitudes of both the roll motion and the vertical oscillation of the robot's body, which led to a noticeable vibration of the robot during locomotion. However, the robot with compliant independent legs (type 2), showed a behavior in-between the other two types of legs.

ACKNOWLEDGMENT

This research was partially supported by JSPS, Grants-in-Aid for Scientific Research, Grant number JP17H04698.

REFERENCES

[1] N. A. Bernstein, (translated from the Russian by M.L. Latash and edited by M.L. Latash and M.T. Turvey). Dexterity and Its Development. Lawrence Erlbaum Associates, Mahmash, New Jersey, 1996.

[2] S. Collins, A. Ruina, R. Tedrake, & M. Wisse, Efficient bipedal robots based on passive-dynamic walkers. Science, 307, 1082-1085, 2005.

[3] T. McGeer, Passive dynamic walking. The International Journal of Robotics Research, 9(2), 62-82, 1990.

[4] D. Torricelli, J. Gonzalez, M. Weckx, R. Jimenez-Fabia n, B. Vanderborght, M. Sartori, & . . . J. L. Pons, Human-like compliant locomotion: State of the art of robotic implementations. Bioinspiration & Biomimetics, 11, Article 051002, 2016.

[5] K. Kaneko, F. Kanehiro, S. Kajita, H. Hirukawa, T. Kawasaki, M. Hirata, & . . . T. Isozumi, Humanoid robot HRP-2. Proceedings of 2004 IEEE International Conference on Robotics and Automation (ICRA), New Orleans, LA, 2004, April 26- May 1.

[6] M. Hirose, & K. Ogawa, Honda humanoid robots development. Philosophical Transactions of the Royal Society A, 365, 11-19, 2007.

[7] R. Pfeifer, & J. Bongard, How the body shapes the way we think: A new view of intelligence. Cambridge, MA: The MIT Press, 2006.

[8] K. Narioka, A. Rosendo, A. Sprowitz, & K. Hosoda, Development of a minimalistic pneumatic quadruped robot for fast locomotion. In Proceedings of the IEEE International Conference on Robotics and Biomimetics, Guangzhou, China, 11-14 December 2012. (pp. 307-311), 2012.

[9] A. Sprowitz, A. Tuleu, M. Vespignani, M. Ajallooeian, E. Badri, & A. J. Ijspeert, Towards dynamic trot gait locomotion: Design, control, and experiments with Cheetah-cub, a compliant quadruped robot. The International Journal of Robotics Research, 32, 932-950, 2013.

[10] S. H. Collins, M. Wisse, & A. Ruina, A three dimensional passive-dynamic walking robot with two legs and knees. The International Journal of Robotics Research, 20, 607-615, 2001.

[11] R. Tedrake, T. W. Zhang, M. Fong, & H. S. Seung, Actuating a simple 3D passive dynamic walker. Proceedings of IEEE International Conference on Robotics and Automation, New Orleans, LA, 2004.

[12] H. Geyer, A. Seyfarth, & R. Blickhan, Compliant leg behaviour explains basic dynamics of walking and running. Proceedings of the Royal Society B: Biological Sciences, 273, 2861-2867, 2006.

[13] G. A. Pratt, & M. M. Williamson, Series elastic actuators. Proceedings of IEEE International Conference on Intelligent Robots and Systems, Pittsburgh, PA, 1995, August 5-9.

[14] B. Vanderborght, A. Albu-Schaeffer, A. Bicchi, E. Burdet, D. G. Caldwell, R. Carloni, & . . . S. Wolf, Variable impedance actuators: A review. Robotics and Autonomous Systems, 61, 1601-1614, 2013.

[15] D. Hobbelen, T. De Boer, & M. Wisse, System overview of bipedal robots flame and TUlip: Tailor-made for limit cycle walking. IEEE/RSJ International Conference on Intelligent Robots and Systems, Nice, France, 2008, September 22-26.

[16] K. Hosoda, & K. Narioka, Synergistic 3D limit cycle walking of an anthropomorphic biped robot. Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, San Diego, CA, 2007, October 29-November 2.

[17] K. Hosoda, T. Takuma, A. Nakamoto, & S. Hayashi, Biped robot design powered by antagonistic pneumatic actuators for multi-modal locomotion. Robotics and Autonomous Systems, 56, 46-53, 2008.

[18] Y. Huang, B. Vanderborght, R. VanHam, Q. Wang, M. Van- Damme, G. Xie, & D. Lefeber, Step length and velocity control of a dynamic bipedal walking robot with adaptable compliant joints. IEEE/ASME Transactions on Mechatronics, 18, 598-611, 2013.

[19] H. Ryu, Y. Nakata, Y. Nakamura, & H. Ishiguro, Adaptive whole-body dynamics: An actuator network system for orchestrating multijoint movements. Robotics & Automation Magazine, 14(8), 85-92, 2015.

[20] H. Ryu, Y. Nakata, Y. Nakamura, & H. Ishiguro, Adaptive locomotion by two types of legged robots with an actuator network system. IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Daejeon, South Korea, 2016, October 9-14.

[21] H. Kim, J. Choi, & T. Seo, Optimal Design of Klann-based walking Mechanism for Water-running Robots. The 14th IFToMM World Congress, Taipei, Taiwan, 2015.