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RESEARCH ARTICLE

Adjustable whole-body dynamics for adaptive locomotion: the influence of upper body movements and its interactions with the lower body parts on the stable locomotion of a simple bipedal robot

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Abstract
This paper investigates the influence of adding an upper body to a bipedal robot on its stable walking behavior. The robot's parts are mutually interconnected through an actuator network system. Therefore, the movement pattern of the upper body depends on the type of interactions created with other limbs. Throughout the experiments, various interactions among the different body parts were tested. The results showed that a robot with a motionless upper body exhibited unstable walking behavior. However, once the same upper body was involved and interacted properly, with other body parts, its movement significantly helped to stabilize the behavior of the robot.

1. Introduction
A human body functions optimally when all the parts operate together as a coherent unit [1]. Therefore, it is crucial for there to be interaction among the various interconnected parts of the body in order for the body to acquire adaptive behaviors during locomotion [2]. The natural and adaptable walking performance of humans is not merely a result of the dynamics generated by the lower body parts; various interactions with different body parts are involved as well. For example, several studies showed that the movements of the upper body make a significant contribution to dynamic balance during locomotion [3, 4, 5], even contributing to stable walking to a similar extent as the lower body, especially during challenging locomotion tasks [3].

The seemingly simple walking behavior of humans includes many complex interactions among various body parts which make it possible [6]. It is therefore not easy to realize robots with adaptive walking capabilities. With this in mind, a lot of studies have been conducted which attempt to shorten the gap in performance between robots and humans [7, 8]. For this purpose, two main schemes of research are followed, numerical computation and morphological computation [9].

From this perspective of the necessity of a bipedal robot having its parts mutually interconnected in order to realize the direct interaction between these parts which facilitates more adaptable walking behaviors, we developed our bipedal robot PedestriANS [10]. This robot utilized the principle of actuator network system (ANS) to manipulate its whole-body dynamics. It could adaptively change the type of interactions between its interconnected legs, as well as adjusting their physical characteristics such as stiffness and damping. The ANS of PedestriANS is composed of two linear actuators that are mutually interconnected through a simplified network of tubes and valves which execute basic on/off

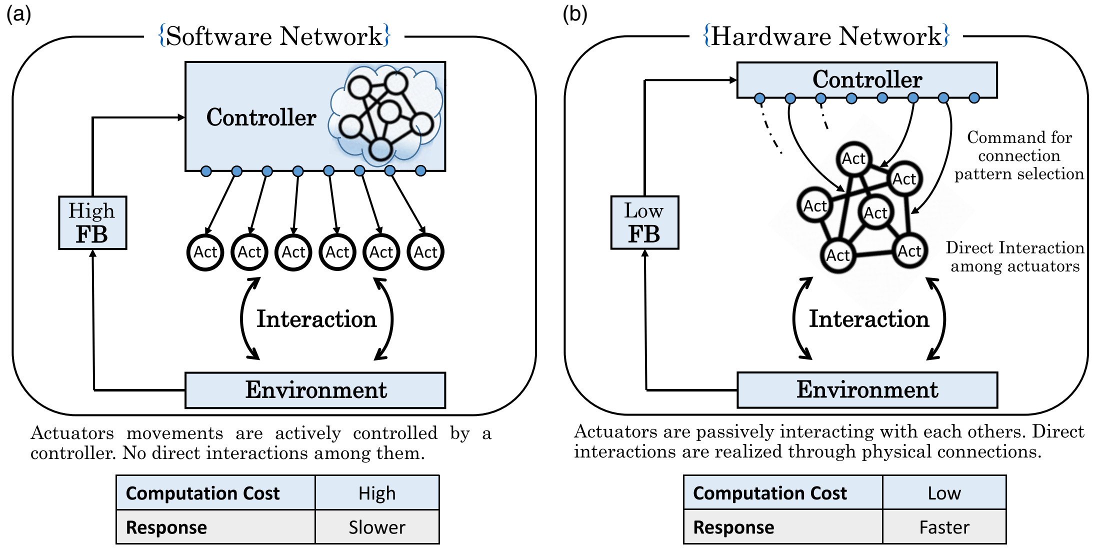

Figure 1. *Connections for adaptive locomotion: comparison between implementing (a) software network of virtual connections among several actuators of a robotic system and (b) hardware network of physical connections.*

switching between the robot's legs. Even though it had limited options for changing the connection patterns between the actuators, the robot was able to respectively adapt its whole-body dynamics to generate better walking behaviors over a variety of different environments.

In order to test our hypothesis that "it is crucial for the robot to engage the movements of all its body parts to realize adaptive locomotion, and that they must be coordinated properly with one another through direct spontaneous interactions based on the gait requirements and the environment in which the robot is operating," we are upgrading the structure design of PedestriANS to enhance the whole-body passive dynamics by extending its ANS system to include the upper body. This will allow us to examine more complex connections and study their effects on modulating opposing dynamic behaviors (e.g., stability, agility, maneuverability, speed, and efficiency).

The effect of the upper body on the dynamics of bipedal robots has been investigated throughout the years by implementing mechanisms with varying levels of complexity and different control strategies [11, 12]. Proper integration between the upper and lower body parts can enhance the stability, efficiency, and speed of bipedal robots [13]. However, to the best of our knowledge, the effect of direct changeable connections between the upper and lower body parts has not been studied before. Here in this paper, as a case study for adaptive behaviors, we investigate the influence of the added upper body movements and its interaction with the lower body parts on the stable walking performance of the robot. The added upper body forms a simple pendulum moving in the frontal plane of the robot; its oscillation direction and the magnitude of its rotational angle depend directly on the connection pattern type of the ANS. Initially, we conducted our experiments without including the upper body with the robot's ANS. This means that no mutual interactions between the robot's legs and the upper body are involved, allowing us to understand the effects of adding an independent motionless upper body on the robot's walking behavior. After that, we extended the ANS to include the upper body of the robot in order to create a body where all parts are interconnected, and multiple interactions are possible among all of them. We therefore conducted experiments involving different connection patterns between the upper and lower body parts in order to examine how upper body movements enhance stability during locomotion.

To see the novelty of our research and to better understand the reasons behind using the concept of ANS in our study, Fig. 1 compares the difference between implementing a hardware network of physically connected actuators of a robotic system and a software network of virtually connected actuators.

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Under software networks, as demonstrated in Fig. 1(a), there are no direct interactions among the actuators. Therefore, the controller itself will create "virtual" connections among the actuators, then send its control signals to each actuator "separately" to "actively control" their interactions with the environment based on the feedback signals that are received from the mounted sensors. The control process followed in this approach is computationally expensive, and the actuators' response to environmental changes is slower (i.e., the actuators will interact with each other and with the environment based on the control signals from the controller which is decided based on the feedback signal coming from the environment). This method is a representation of the numerical computation scheme; and mainstream bipedal robots such as Honda's ASIMO [14], NAO [15], and the HRP series of robots [16] are examples of robots belonging to this scheme. Although these robots showed remarkable locomotion performances, explicit models of the robot's body and the environment in which it is operating are essential to realizing adaptability. Hence, if changes occur to the surroundings, a robot following this approach will lose its stability.

On the other hand, with the hardware networks of physically connected actuators, which represent the concept of ANS, direct interactions are established among the actuators as can be seen in Fig. 1(b). Therefore, the movement patterns of these actuators (the ways they interact with each other) are directly influenced by the type of connection patterns among the actuators themselves, as well as their interaction with the surrounding environment. The computational cost for this approach is low, and actuators have a faster response to environmental changes (i.e., actuators spontaneously and passively react to environmental changes).

ANS implementation is classified under the morphological computation scheme, since it gives more focus to the mechanical design of the robot. Yet it differs from other robots following the same scheme by creating an adaptive morphology capable of exploiting whole-body dynamics through realizing three primary characteristics: (1) changeable interactions between the different body parts of the robot, (2) adjustable physical characteristics (e.g., stiffness and damping), and (3) spontaneous passive interaction with the environment. A typical example of robots following the morphological approach is the passive dynamic worker [17]. This is an energy-efficient robot that exploits the mechanical structure of its body (balances by using counter-swing of the arms that are attached rigidly to their opposing legs) to demonstrate a natural-looking walking behavior without any active control, actuation, or power input (powered only by gravity). However, this robot cannot generate versatile locomotion gaits and its stable walking behavior is limited to a narrow range of environmental conditions due to the lack of actuation and the ability to alter interactions between its parts.

The rest of the paper is structured as follows. Section 2 introduces the mechanical structure of the robot, both its upper and lower body parts, and explains in detail its ANS. Section 3 presents the types of connection patterns that were tested during the experiments, clarifies the experimental setups and procedures, and demonstrates the obtained results. Section 4 discusses the results and points for some areas of research for future work. Section 5 provides the conclusion of the paper.

2. The upper and lower body parts of the robot and their ANS connections

Basic adaption to environmental changes by employing an ANS was proven in our previous research, with experiments being conducted using a simple bipedal robot on various ground materials [10]. Although the coupled ANS with the robot was confined to limited connection patterns between its legs, the experimental results clearly showed that the robot would change its behavior by varying the type of interaction between its legs, and that the demands for a certain connection pattern to produce better performance differs based on the given situation.

To take a step forward towards our ultimate goal of developing robust robots that can accompany humans, capable of operating in unstructured environments, and able to safely interact with the inevitable physical contact with the surroundings, the ANS should be expanded and encompass all body parts to improve the whole-body passive dynamics. Thus, in this section, we will introduce the upgraded robotic structure, the extended ANS of the robot that includes its upper body, and explain how various types of

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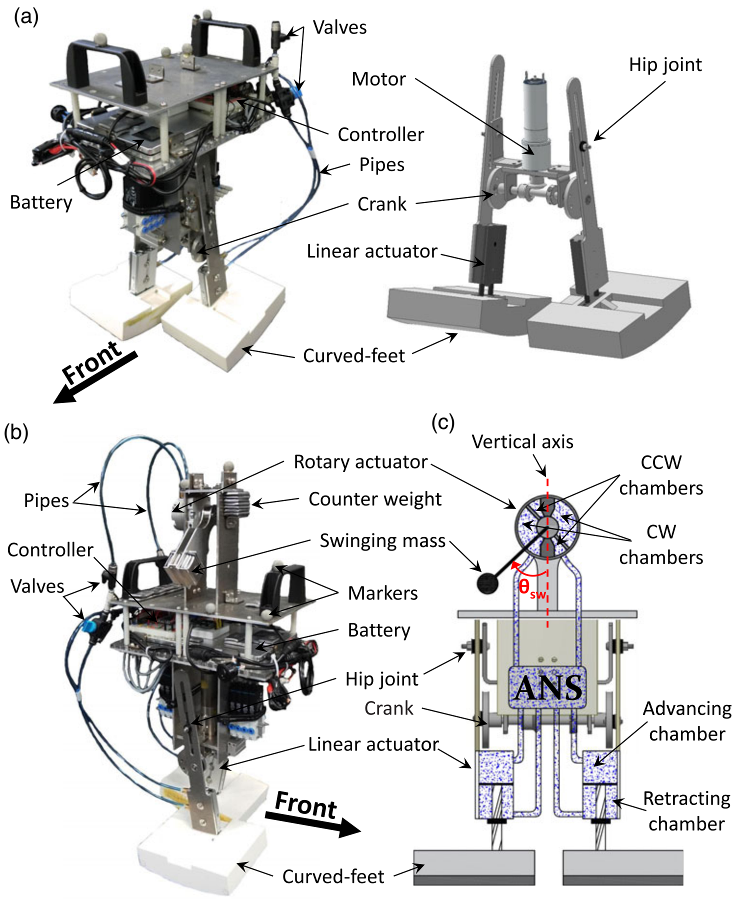

Figure 2. *(a) Mechanical structure of the robot without an upper body. (b) The updated robot with upper body. (c) Illustration of the actuator network system (ANS). θsw: Swing angle with respect to the vertical axis, positive in the clockwise direction.*

interactions with more complex connection patterns can now be tested to study their influence on the robot's adaptive behavior while taking the stability performance as a case study.

2.1. Structure of the robot

The lower body parts of PedestriANS consist of two identical legs that are coupled at the crank with 180° out phase, as shown in Fig. 2(a). Each leg represents an inverted slider-crank mechanism, which is a four-bar linkage coordinated by a single degree of freedom [18]. A dual-rod pneumatic cylinder with a linear motion range of (20 mm) is fixed at the lower end of each leg; it creates an adjustable compliant leg and forms an element of the ANS. The robot's feet are attached to the legs through these pneumatic cylinders, as shown in the figure. The curved shape of the feet provides gentler gate patterns and reduces collision strike against the ground. The whole-body movement of the robot is generated by a single DC motor (24 V) and controlled by an Mbed microcontroller that is mounted on the robot's body as illustrated in the figure.

The upper body of the robot was built to create a robotic structure where all parts are mutually interconnected to investigate more complex connection patterns and their influence on the robot's locomotion behavior. It consists of a swinging mass, weighing 200 g, hanging down from a rotary actuator with a radius length of 101 mm, as shown in Fig. 2(b). The actuator position on top of the robot allows the

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swinging to happen in the frontal plane above the robot's center of mass (CoM). As demonstrated in Fig. 2(c), it is a double-vane rotary actuator with an angular rotation range of (± 50°) from the vertical axis. Similar to the linear actuators fixed on the robot's legs, it is associated with the robot's ANS. Therefore, the movement patterns of its swinging mass (the way it oscillates) depends directly on the type of connection pattern among the actuators. Note that all actuators of the ANS are entirely passive, and no energy is supplied into the system; their movements and interactions during locomotion are simply caused by the collision impact forces of the robot's feet against the ground.

2.2. Actuator network system

ANS was proposed in previous research and implemented in different applications, such as building a robotic spine [19], arm [20], and multi-legged robots [21]. As the term implies, ANS consists of actuators that are mutually connected through a network of pipes and valves. Corresponding to each connection pattern among the actuators, distinct dynamics of the robot's body will be produced.

The updated ANS of PedestriANS includes three actuators, as demonstrated in Fig. 2(c). Two linear actuators are attached to the robot's legs, and one rotary actuator is mounted on top of the robot and responsible for the oscillatory movement of the swinging mass. The linear actuator is composed of two chambers, the proximal chamber (advancing) and the distal chamber (retracting). The compliance adjustment and the movement of its rod (piston) depend on the air pressure difference between the two chambers. Higher pressure inside the proximal chamber compared to the distal one will cause an extension of the robot's leg, and retraction happens once the distal chamber has a higher pressure. The same concept is also applied to the rotary actuator. However, the difference here is that rotational movements are generated instead of the linear ones, and based on the pressure difference between the chambers, the mass will rotate in a clockwise (CW) direction or a counterclockwise (CCW).

The various arrangements of the valve system are what create the differences in the robot's behavior. With every set of switched valves (opened/closed), unique interactions among the actuators will affect the robot's dynamics. For example, closing all valves will create an independent movement for each body part. On the other hand, a specific combination of open valves will produce mutually interconnected parts with a particular interaction among them. Therefore, the whole-body dynamics of the robot are influenced by the type of interactions among the actuators themselves, as well as their interaction with the surrounding environment during locomotion. And the compliance/stiffness of the actuators is adjusted by the air pressure value of the ANS.

More details about the different connection patterns of the ANS can be found in the next section.

3. Analyzing the effects of various interactions among the different body parts of the robot on its walking behavior

3.1. Connection patterns

To examine how the upper body movements would affect the stable walking behavior of the robot, various connection patterns between the lower and upper body parts were tested throughout the experiments. The experiments were conducted under three groups of connection patterns, without an upper body mass, with a motionless (fixed) upper body mass, and with a moving upper body (MUB). Note that a unique air pressure value of the ANS was selected for each connection pattern to get the best possible performance out of it.

3.1.1. Group 1, No upper body mass (NUB)

Before adding an upper body mass on top of the robot, experiments were conducted to set a baseline for our comparisons. Two types of connection patterns were tested within this group as shown in Fig. 3(a). Under type 1, mutually connected legs, the air pressure inside the cylinders was adjusted to position the legs at their half-advanced lengths. Then, with a certain combination of open/close valves of the

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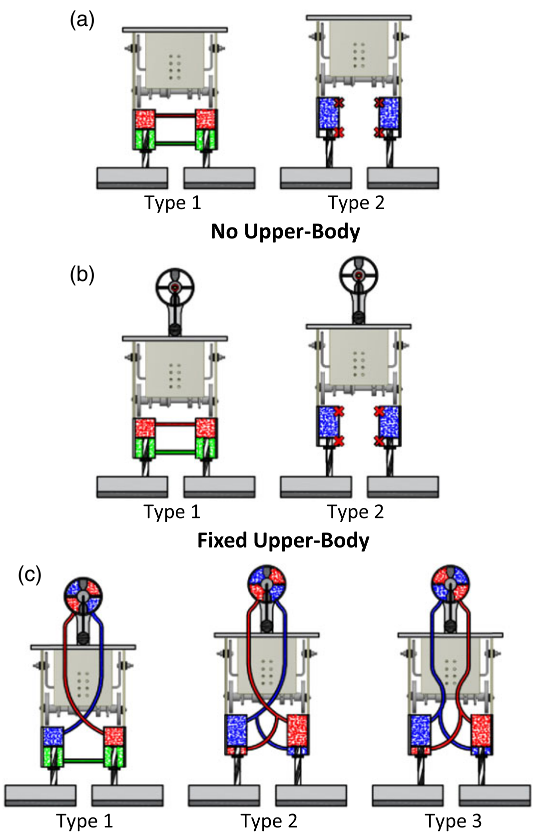

Figure 3. *The applied connection patterns during experiments with their corresponding initial body posture of the robot. (a) Group 1 connections with no installed upper body. Under type 1, the legs are mutually connected and set to their half-advanced lengths. Under type 2, the legs are independent, fully extended, and compliant. (b) Group 2 connections with a motionless upper body. The legs under type 1 are mutually connected and set to their half-advanced lengths. Under type 2, the legs are independent, fully extended, and compliant. (c) Group 3 connections with a moving upper body. Under type 1, legs are set to their half-advanced lengths, the swinging mass is hanging along the vertical axis, and the interactions are happening among all actuators. Under types 2 and 3, interactions occur between each leg and the swinging mass, with no interaction between the compliant legs; the difference between them is the rotation direction of the swinging mass.*

ANS, we allowed force transfer between the two legs. In this case, the movement of one leg will affect the other one. For example, as the left leg fully retracts during its stance phase, the right leg will fully expand during its swing phase.

Under type 2, independent compliant legs, both cylinders are fully extended by pressurizing the proximal (advancing) chambers with higher pressure value compared to the distal (retracting) ones. The valves of ANS are then kept closed to prevent any direct interaction between the two legs, as demonstrated in the figure.

3.1.2. Group 2, fixed upper body mass (FUB)

The purpose of this group of connection patterns is to investigate the effects of adding a motionless upper body mass to the robot. The stability performance of the robot was compared to the connection

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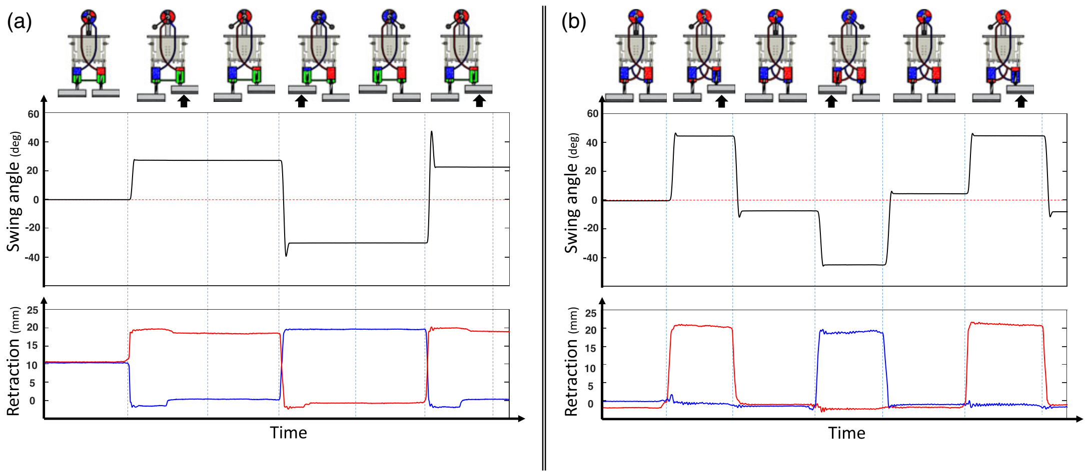

Figure 4. *The manner of interaction between the lower and upper body parts for (a) under the type 1 connection of Group 3 (MUB), and (b) under type 2. The graphs at the bottom show the legs movements (expansion/retraction). The graphs in the middle show the response of the swinging mass to the legs movements. The figures on the top show the corresponding body postures of the robot and are arranged from left to right as follows: initial posture, applying an external force to the left leg, removing the applied force, applying an external force to the right leg, removing the applied force, then repeat the cycle. The red line represents the left leg. The blue line represents the right leg. The horizontal dashed line at angle = 0° represents the vertical axis of the robot. A positive swing angle indicates rotation in the clockwise direction, while a negative angle means a counterclockwise rotation.*

patterns of Group 1 (NUB). During the experiments conducted within this group, NUB movement was involved during the robot's locomotion. The swinging mass was mechanically fixed as illustrated in Fig. 3(b). Similar to Group 1, two types of connection patterns were tested, mutually connected legs (type 1) and independent compliant legs (type 2). Both types of connections have no direct interaction with the upper body as shown in the figures.

3.1.3. Group 3, moving upper body mass

In this group of connections, the movement of the swinging mass contributes to the whole-body dynamics of the robot and affects its walking behavior. The manner of its swinging relates directly to how the rotary actuator is connected to the rest of the ANS components. Three types of connection patterns belonging to this group were tested during the conducted experiment. Under type 1, the air pressure inside the ANS is adjusted to set the robot's legs at their half-advanced lengths, and the swinging mass hangs down along the vertical axis (0° from the vertical axis). After that, the valve system of the ANS is switched in a way to create the connection pattern demonstrated in Fig. 3(c). In this case, mutual interactions are realized among all actuators of the ANS, between the two legs, as well as between each leg and the swinging mass. Their manner of interaction is demonstrated in Fig. 4(a). For example, as the left leg fully retracts during its stance phase, it causes the right leg to fully expand and simultaneously rotates the swinging mass 27° in the CW direction (an opposing direction to the stance leg).

In the type 2 situation, shown in Fig. 3(c), the air pressure of the ANS is adjusted to create fully expanded legs during the robot's initial posture while the swinging mass hangs down along the vertical axis. Similar to type 1 of the same group, the interaction between each leg and the upper body induces the swinging mass to rotate in the opposite direction to the stance leg. However, in this case, there is no "noticeable" interaction between the two legs as illustrated in Fig. 4(b). For example, the retraction of the left leg will cause the swinging mass to rotate 45° in the CW direction without any noticeable effect on the right leg.

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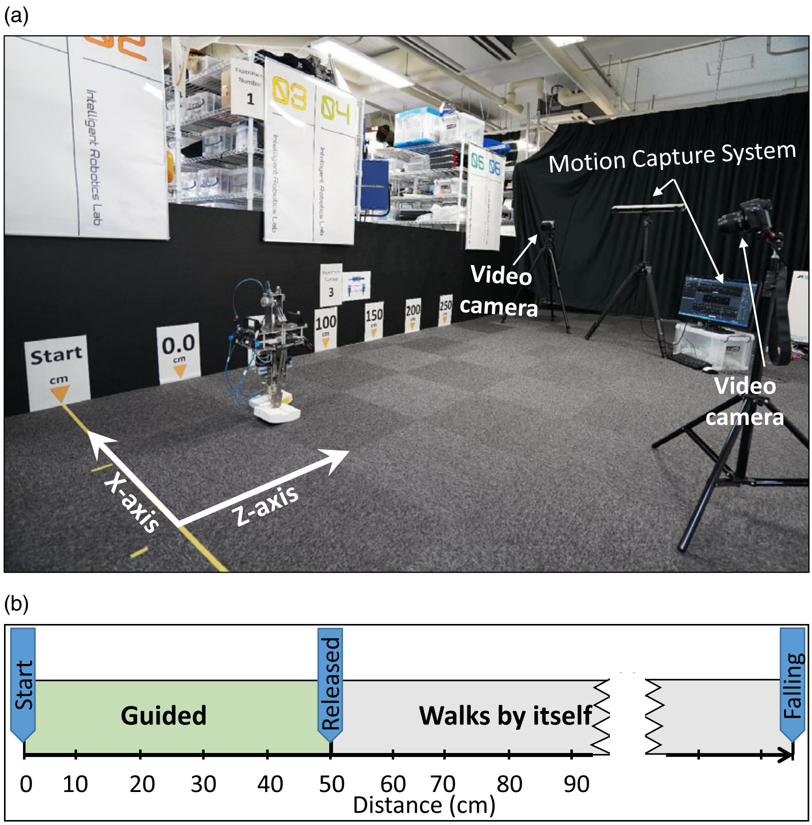

Figure 5. *(a) Experimental environment. (b) Experimental design.*

Under type 3 connection, the legs are fully extended while the swinging mass hangs down along the vertical axis during the initial posture of the robot. While there is no noticeable interaction between the two legs, contrary to type 2 connection, the swinging mass rotates in the same direction with respect to the stance leg. For example, as the left leg hits the ground during locomotion and fully retracts, the swinging mass will rotate 45° in the CCW direction while no effect is observed on the movement of the right leg.

3.2. Experimental setups and procedures

The experiments were conducted in order to investigate how the different upper body interactions with lower body will influence the stable walking behavior of the robot. For each of the previously mentioned seven connection patterns, the following procedures were implemented during each trial:

1. Adjust the air pressure of the ANS and manually switch the valves to one of the connection pattern types.
2. Operate the robot, put it on the ground, and then guide its movement direction for the first (0.5 m) of its locomotion as shown in Fig. 5(b).
3. Release the robot and let it move by itself without guidance until it falls down.
4. Repeat the experiment three times for each type of connection patterns to ensure the reproducibility of the results.

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Table I. *Numerical summary of the obtained results.*

Group	Connection	Traveled distance (m) ± S.D.	Deviation angle (deg) ± S.D.	Roll (deg) ± S.D.	Yaw (deg) ± S.D.
(1) No upper body	Type1	Did not fall	–9.04 ± 0.57	9.47 ± 1.11	11.51 ± 3.08
	Type2	2.12 ± 0.08	+7.94 ± 2.44	7.49 ± 1.02	16.88 ± 2.21
(2) Fixed upper body	Type1	0.92 ± 0.17	–0.04 ± 2.91	6.98 ± 1.28	15.41 ± 1.16
	Type2	0.84 ± 0.11	+2.92 ± 2.78	6.05 ± 2.12	15.60 ± 1.65
(3) Moving upper body	Type1	2.03 ± 0.08	+0.14 ± 1.51	8.01 ± 0.92	11.74 ± 3.26
	Type2	2.27 ± 0.12	+9.52 ± 2.70	7.20 ± 0.99	17.78 ± 2.88
	Type3	0.68 ± 0.02	+4.02 ± 4.51	6.47 ± 2.01	18.56 ± 2.55

The data cover both the guided and unguided periods. The positive sign of the deviation angle indicates a deviation to the left side with respect to the movement direction, while the negative sign means turning to the right side. The range of the Roll and Yaw motions is defined as the difference between every two successive peaks.

The experiments were performed on a carpet ground material as shown in Fig. 5(a). Reflective markers were installed on the robot's body, as illustrated in Fig. 2, to analyze its dynamics during locomotion. An OptiTrack-V120: TRIO motion capture system was employed to record and track these markers.

3.3. Results

The evaluation of the robot's performance during the experiments was made by observing the distance traveled by the robot before falling down. This evaluation determines the effects of the applied connection patterns of the ANS on the stable walking behavior of the robot. The longer the distance traveled by the robot before falling down, the more stable it is.

Three trials were conducted for each of the previously mentioned seven types of connection patterns. The graphs of Fig. 6 show the walking paths of all experiments during the robot's locomotion. They show the distance traveled by the robot as well as the movement direction. As can be deduced from the graphs of Group 1 (NUB) connections, the robot without an upper body mass realized a stable walking behavior under both types. Under type 1, mutually connected legs, the robot did not fall during any trial; while under type 2, with independent compliant legs, the robot traveled a distance of (2.12 ± 0.08 m) before falling down as depicted in Table I. However, both types of this group showed a deviation in their movement directions; type 1 turned (9.04 ± 0.57°) to the right during all trials, while type 2 kept turning to the left with a deviation angle of (7.94 ± 2.44°).

Once a motionless upper body mass was added on top of the robot, the robot directly lost its stable behavior. This is evident from the graphs of Group 2 (FUB) connections; regardless of the connection pattern used between the robot's legs, the robot was only able to move few steps before falling down after it was left to walk by itself without guidance, as demonstrated in the table.

On the other hand, the robot recovered its balance back and gained other preferences as well after involving the swinging mass movement of its upper body. With mutually connected legs, and a swinging mass moving in an opposing direction to the stance leg, the robot under type 1 of Group 3 (MUB) connections managed to travel (2.03 ± 0.08 m) before falling down as Table I shows. Not only that but it also managed to maintain its moving direction and kept walking straight along the Z-axis, as illustrated in the graphs of Fig. 6(c). Under type 2 of the same group, with no noticeable interactions between the two compliant legs, the robot also exhibited stable behavior by walking (2.27 ± 0.12 m) before falling down. However, during locomotion, the robot slightly deviated to the left side with an angle of (9.52 ± 2.70°) from the straight path direction. In contrast, with type 3 connection, the interaction between each leg and the upper body causes the swinging mass to oscillate in the same direction with respect to the stance leg. In this case, the robot showed the most unstable behavior among all connection patterns, as shown in the table; it directly fell down after it was left to walk by itself without guidance.

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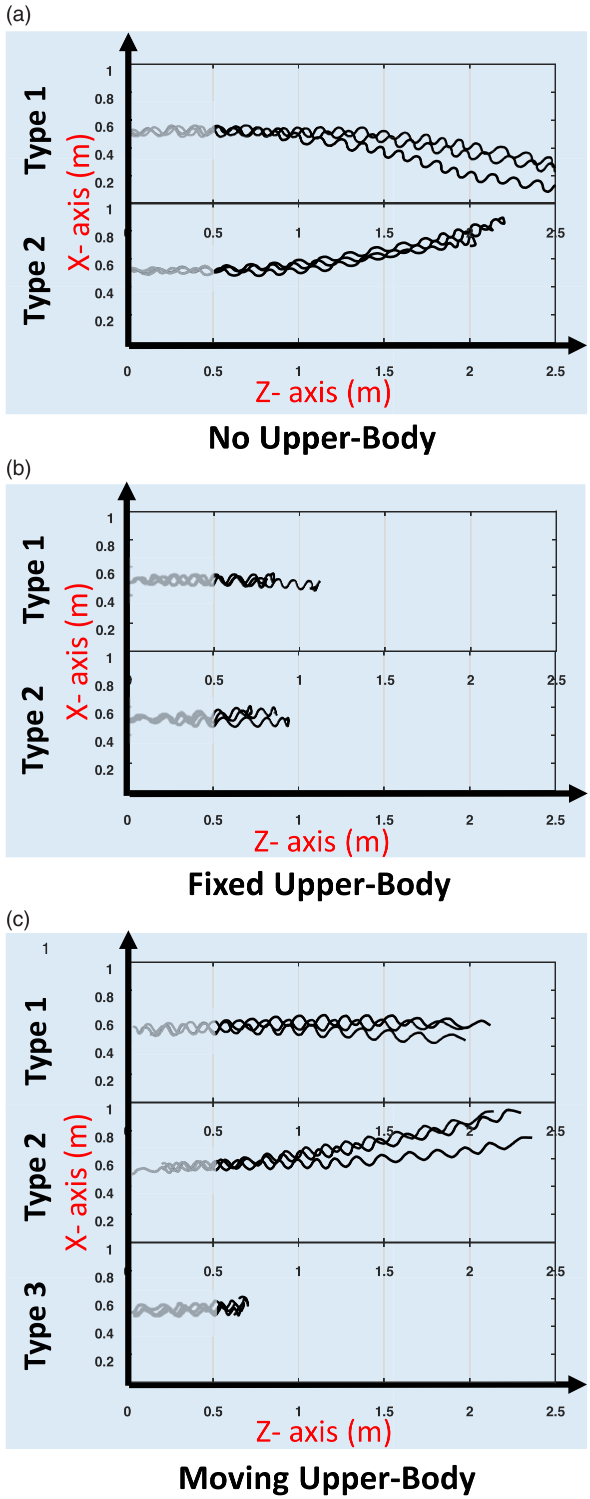

Figure 6. *Graphs of the waking paths traveled by the robot during all trials for (a) Group 1 connections with no upper body attached, (b) Group 2 connections with a fixed (motionless) upper body, and (c) Group 3 connections with a moving upper body. The faded part at the beginning of each graph (from 0 to 0.5 m) represents the guided period of the robot.*

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4. Discussion

If the elements of high-speed processing, precise sensing, and accurate modeling of the surroundings are established, then using a supercomputer under the conventional approach of actively controlled actuators could be the best solution to realize robots able to interact properly with various environments. However, this is not a practical solution due to the high computational complexity involved. Therefore, to overcome this problem, we are proposing the principle of ANS to create robotic systems capable of interacting with changing environments through passive interactions. Hence, with such systems, robots can spontaneously react to environmental changes passively without waiting for the controller to continuously process the surroundings and actively control the actuators at all times.

Unlike other mechanical systems that create fixed relations and constraints among links/joints (e.g., parallel mechanism), ANS can generate various types of interactions among neighboring and distant links/joints alike through its changeable connection patterns. Therefore, this will widen the domain of applications by increasing the range of adjustability that can be performed on the system. An analogy would be something similar to the "Anti-Roll Bar" in automobile suspension systems that connects opposite wheels together to stabilize vehicles over road irregularities, but on a bigger scale that connects all links of a massive system. Therefore, the different connection patterns of an ANS affect the robot's dynamics in various ways by changing the type of interaction between its body parts. For instance, under the independent spring-like leg cases, the retraction/expansion of a swinging leg is independent of the other stance leg. Whereas, in the case of mutually connected legs, the retraction/expansion movement of a swinging leg depends directly on the other stance leg. In light of this, the difference in performance between mutually connected legs and independent compliant legs is not due to a mere difference in compliance; the manner and timing of expansion affect the performance too. Therefore, each of these types of legs shows distinct effects on the gait cycle (e.g., the periods of single- and double-limb support), angular momentum, rotational slip caused by the yaw moment on the stance leg, ground reaction forces, positioning the robot's CoM, and so forth. The same also applies when engaging the upper body; each connection pattern will have different effects on the swinging mass's rotational direction, angle, and speed, which consequently produces different body dynamics.

The conducted experiments demonstrate the importance of having interconnected parts for achieving adaptive walking behavior. The graphs of Fig. 7 clearly show how changing the type of passive interaction between the body parts influences the robot's dynamics. Adding a FUB on top of the robot without interactions with other parts caused the robot to lose its stability. However, once the same upper body was involved and interacted with other body parts, its movement helped to recover the stable behavior of the robot. The significance of having mutually connected parts was shown in the results of every group of connection patterns; the robot with mutually connected legs (type 1) showed better performance compared to independent legs (type 2) for both Groups 1 (NUB) and 2 (FUB). The same is also applied to Group 3 (MUB) of connection patterns; the robot realizes better performances with the proper selection of interactions among its parts.

Knowing that the circular shape of the robot's feet was optimized for the robot with NUB, increasing the height of the CoM by adding an upper body without changing the feet size will reduce the stability performance of the robot. This is because smaller tilt angles will now cause the CoM to leave the base of support. Hence, the second group of connections (FUB) established unstable behavior; as the lower body moves forward, the upper part of the body tends to remain at rest due to inertia. Therefore, under the connection patterns of the FUB group, the robot always fell in the backward direction after moving few steps, as shown in the pitch motion graphs of Fig. 7(b). On the other hand, the robot under the third group of connections (MUB) realized better adaptive behaviors, although it also had a high CoM position. The whole-body dynamics generated from the passive interaction between the lower and upper body parts, specifically in type 1 and type 2, resisted the robot's tendency to fall in the backward direction. As a result, the robot did not fall backward and managed to travel a longer distance as demonstrated in Fig. 6(c). However, due to the simple mechanism of the upper body, the robot eventually fell down but in the forward direction as shown in the pitch motion graphs of Fig. 7(c).

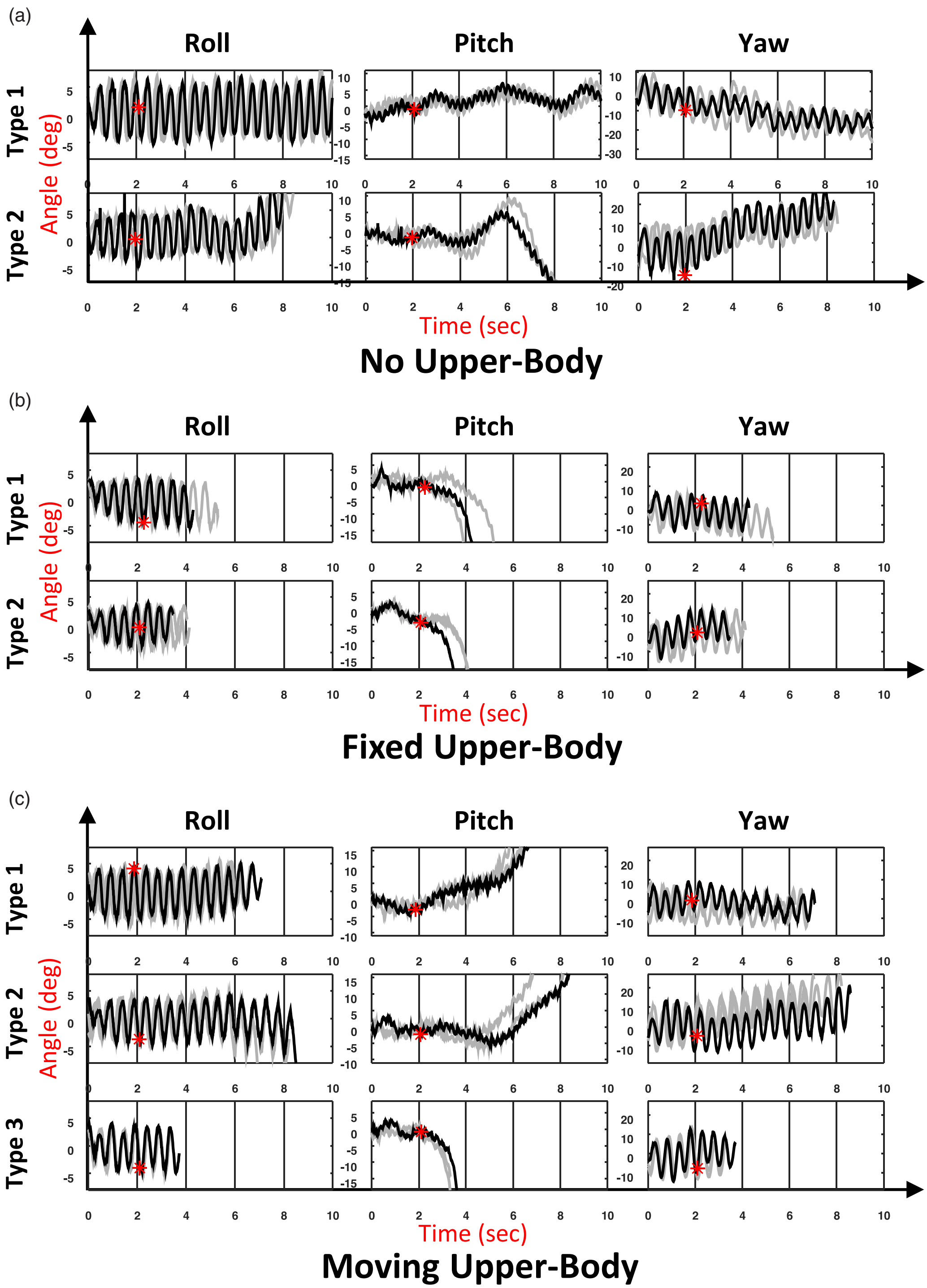

Figure 7. *Graphs of the roll motion, pitch motion, and yaw motion of the robot's body during all trials. (a) Group 1 connections with no upper body. (b) Group 2 connections with a motionless upper body. (c) Group 3 connections with a moving upper body. For each connection pattern, one of the three conducted trials is highlighted in black color, while the rest are plotted in gray. "∗" Indicates the end of the guided period.*

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The movement of the swinging mass in an opposing direction to the stance leg in Group 3, type 1 connection, where mutual interactions are happening between all actuators, caused a maximum roll motion of ($8.01 \pm 0.92°$) compared to the other types of connections in Groups 2 and 3, as illustrated in Table I. Simultaneously, the robot produced a minimum yaw motion of ($11.74 \pm 3.26°$) that allowed the robot from maintaining its moving direction as shown in the walking path graphs of Fig. 6(c) and the yaw motion graphs of Fig. 7(c).

Both type 1 and type 2 connections of Group 3 (MUB) caused the swinging mass to rotate in an opposing direction to the stance leg. However, the amplitude of the rotation angles is different, as can be seen in the graphs of Fig. 4. These differences in the interactions among the body parts caused the robot to gain different benefits. The robot under type 2 connection traveled a relatively longer distance, while under type 1, the robot maintained its moving direction. Therefore, selecting the type of interactions among the different parts should correspond to the gate requirements. And this is similar to what happens during human locomotion; the frequency and amplitude of the arms movements are adaptive to the gait conditions. For example, the amplitude of the arm swing increases proportionally to the walking speed [22].

Simplifying the upper body motion to a single pendulum with mass is an approximate representation of the changes occurring to the CoM position caused by the upper body movement. Indeed, the shape and motion of the upper body of real humans are more complex and allow the CoM position to oscillate in a 3D space [23]. However, for simplicity purposes, we only considered the effect of the CoM oscillation in the frontal plane, especially, knowing that the movement of the upper body in this plane has a significant effect on the walking gate. For example, the lateral movement of the upper body stabilizes the side-to-side tilting [24], while the counter-swinging reduces the angular momentum around the vertical axis [17]. In this research, we do not try to achieve perfect imitation of human dynamics, but rather to get insights from how the human body functions to enhance the adaptive performance of robots. Therefore, these simple mechanisms are necessary to examine the feasibility of implementing new ideas before moving to complex systems. The primitive structure of the added upper body with ANS demonstrated the possible enhancements in performance that could be acquired by utilizing its interactions with other limbs. However, the advantages gained by the current upper body are limited due to its simplicity. Therefore, upgrading the robot's mechanical structure to include more parts, such as trunk and arms, and expanding the ANS will increase the types of interactions among the interconnected parts. Accordingly, this will reflect on the adaptive walking behavior of the robot.

Switching between the different connection patterns of the ANS was done manually prior to each experiment. Thus, the robot retained the predetermined connection pattern without being able to change it during locomotion. However, as mentioned earlier, the type of connection pattern among the body parts should be selected to suit the gait conditions. Therefore, in future work, we will replace the manually actuated valves with electronically actuated ones and realize a control system where the robot can autonomously choose an adequate connection pattern and operate without continuous human input and guidance. In addition to this, adjusting the mechanical impedance of the robot's body parts can be utilized to accommodate kinematic variability when confronted with different adaptation demands [25] and enhance stability in response to external perturbations [26]. Impedance modulation, expressed as stiffness and damping, can be investigated in the future by installing an air pump on the robot's body to allow active control of the air pressure inside the different ANS components.

Implementing an ANS provides a subtle equilibrium between robustness and controllability. It allows easier control of large systems of actuators by creating various passive interactions through different connection patterns and adjusting large quantities of actuators with few input signals (e.g., using pneumatic multiplexer). Therefore, these features of the ANS can be utilized in diverse areas of research besides improving the robots' adaptive behaviors to environmental changes. Possible applications that could benefit from ANS could include, but are not limited to, the development of adaptive suspension system for vehicles, body-powered prosthetics, remote manipulation applications, MRI-compatible robots, shapeshifting robots, kinetic arts, modular robots with remote force transmission, and building human-like robots able to interact with humans by generating designated motions through structural constraints and passive interactions with the inevitable physical contact with the surroundings. Moreover, although the current ANS uses a pneumatic-based fluid system for force transmission between actuators, the concept of ANS is not restricted to pneumatic mediums only and it can be expanded to encompass other mediums as well, such as hydraulic and electric systems.

5. Conclusion

In this paper, we studied the effect of expanding an ANS of a bipedal robot by adding an upper body to its structure and investigated its influence on the stable walking behavior as a case study for adaptability. The added upper body forms a swinging mass that oscillates in the frontal plane above the robot's CoM. Its movement pattern (the way it oscillates) depends on the type of interactions created with other limbs, since all body parts are mutually interconnected through an ANS. Although it has a simple structure and its motion is restricted to a single plane, the experimental results clearly demonstrated the significance of engaging upper body movements through its interaction with other body parts during locomotion. Throughout the experiments, the robot with a fixed (motionless) upper body exhibited unstable walking behaviors; however, once the same upper body was involved and interacted properly with other body parts, its movement helped to recover stable behavior for the robot.

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Conflicts of Interest. The authors declare none.

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