PedestriANS: A Bipedal Robot with Adaptive Morphology

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

***Abstract*— In diverse situations, humans produce natural and adaptable bipedal locomotion by cooperatively manipulating the interactions among the different parts of their bodies and the environment. Therefore, to realize a robot with adaptable behavior, it should be enabled to adjust its morphology accordingly in response to environmental changes. From this perspective, this study introduces the development of a bipedal robot with adaptive morphology. By implementing an Actuator Network System (ANS), the robot is able to manipulate the physical characteristics of its legs and the way they interact with each other. Two experiments have been conducted, main and supplementary experiments. The main experiment examined how effective is adjusting the robot's morphology on changing the robot's behavior. The experiment was conducted on different ground materials and under different connection patterns between the robot's legs. During the experiment, the robot's behavior was evaluated in reference to four aspects: walking style, stability, speed, and moving direction. The supplementary experiment took the results of the main experiment and used it to improve the robot's behavior during locomotion. The robot was enabled to automatically switch between the different connection patterns of the ANS, which in turn changed the interaction between the robot's legs, and generated a more suitable dynamics for the surrounding environment.**

I. Introduction

In diverse situations, humans produce natural and adaptable bipedal locomotion by cooperatively manipulating the interactions among the different parts of their bodies and the environment. Therefore, to accommodate different environments, the synergy between the two legs and the way they interact with each other, along with their interactions with other limbs, plays a major role in the adaptive walking behavior of humans [1], [2]. Because of these complex tasks performed by the human's body during locomotion, it is hard to augment bipedal robots with human-like locomotion abilities. For this matter, throughout the years, many researchers have conducted intensive studies to build bipedal robots with gait patterns similar to that of humans [3], [4]. They follow in their research two approaches, the numerical computation approach (conventional), and the embodied intelligence approach (modern) [5].

Many of the robots following the conventional approach have demonstrated impressive and versatile motion behaviors, which made them categorized amongst the most advanced humanoid robots. Examples of these robots are the Humanoid Robot Project's HRP series of robots [6] and Honda's ASIMO [7]. However, accurate models of the robot's own body and its surrounding environment are crucial for these robots to achieve adaptability.

On the other hand, researchers following the embodied intelligence approach have developed robots with efficient and more natural walking behaviors. Oftentimes they get their insights into design concepts and ideas for these robots from nature [8], [9]. They utilize the different mechanical dynamics and the material properties of their bodies and exploit its interaction with the environment to realize efficient behaviors. A common example of these robots are Passive Dynamic Walkers (PDWs) [10], [11], [12]. With their simple mechanical structures, passive dynamic walkers have remarkably shown humanlike motions. It is capable of walking down an incline without any active control or energy input; only gravity and the natural dynamics alone generate the walking cycle. Despite their efficiency, environments in which these robots are capable of operating are confined to inclines of particular slopes. Therefore, these robots are not versatile and lack adaptability to accommodate different environments.

For a robot to realize adaptable behavior, it should be enabled to manipulate its morphology to generate desirable dynamics in response to environmental changes [8], [9]. Based on this view, many studies have addressed this issue by implementing soft materials and variable stiffness actuators [13], [14], [15]. These robots exploited the natural dynamics as it interacts with the environment, and generated more energy-efficient locomotion behaviors [16], [17], [18]. However, while moving within a given environment or during transitioning between different terrains, individually installed parts with variable stiffness actuation may not be sufficient without direct interactions among them. Especially to allow adaptation of opposing dynamic requirements such as stability, maneuverability, efficiency, and speed.

In order to leverage adaptive morphology in robotic systems and allow direct interactions among the different parts of the robot's body, here in this research, we are using the principle of Actuator Network System (ANS). ANS was proposed in previous researches to extend the dynamic performances and provide new functionalities of legged robots by changing the physical characteristics of their bodies [19], [20], [21]. ANS is a closed fluid system. It comprises a set of actuators that are mutually connected through a network of pipes and valves. With different connection patterns among the mounted actuators on the robot's body, it will adaptively change the robot's morphology to create new dynamics and behaviors.

Contrary to other studies that applied ANS on multi-legged robots, here in this research, we are implementing ANS

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for developing a bipedal robot. Moreover, instead of using manually actuated valves for the ANS, which prevented the robots in the previous researches from switching to different connection patterns during locomotion, in this research, we are using electronically actuated valves to test how changing the connection patterns during the robot's locomotion will enhance its performance. The developed bipedal robot "PedestriANS", shown in figure 1-a, uses ANS to change the physical characteristics of its legs and the way they interact with each other. This allows it to overcome the limitations imposed by fixed body structures, broaden its body dynamics, and expand its ecological niche. Hence, the purpose of this research can be summed up under the following hypothesis: The performance of a bipedal robot (that has telescopic legs and semicircular shaped feet) cannot be at its best with a single body morphology whilst operating on different ground materials (slippery, hard, and soft). A robot should realize diverse levels of variable compliance actuation that include not only each part of the robot individually, but exceeds it to the level of whole-body dynamics. Therefore, to achieve optimal robustness of its locomotion gait, a robot needs to adapt its body with different elasticity, stiffness, and interactions among its parts to attain better behaviors in the face of changing environments.

The rest of this paper is organized as follows. Section II introduces the developed bipedal robot "Pedestrians". It demonstrates in details the mechanical structure of its body, and the valve system of its ANS. Section III introduces the main experiment of this paper, the three-tested connection patterns, the experimental settings, procedure, and its results. Section IV explains the experimental settings, procedure, and the results of the supplementary experiment. It also presents the updated version of the robot. Section V discusses the results of both experiments and provides some insights for future work. Section VI concludes the paper.

II. PedestriANS: A Bipedal Robot with ANS

A. Structure of the Robot

The developed bipedal robot "PedestriANS", shown in figure 1-a, is built with a simple structure based on Inverted Slider-Crank mechanism [22]. It is a four-link mechanism with three revolute joints and one prismatic joint as demonstrated in figure 1-b. Two of this mechanism, coupled at the crank and one-half cycle out of phase with each other, create the robot's legs. As both of the cranks rotate, the robot's legs oscillate up and down generating the walking behavior. A 24V DC motor is responsible for the robot's locomotion. The battery, as well as the microcontroller (Mbed), are mounted on top of the robot as illustrated in figure 1-a.

To obtain adjustable compliant legs in addition to mutual interactions between them; a dual rod pneumatic cylinder is added at the end of both legs. Attached to each of the pneumatic cylinders is a semicircular shaped foot, as shown in the figure. This particular shape of the feet was chosen to control the step size and to allow ground clearance during the swing phase of the robot's gait. It also provides a smooth walking behavior as it helps to reduce the collision impact

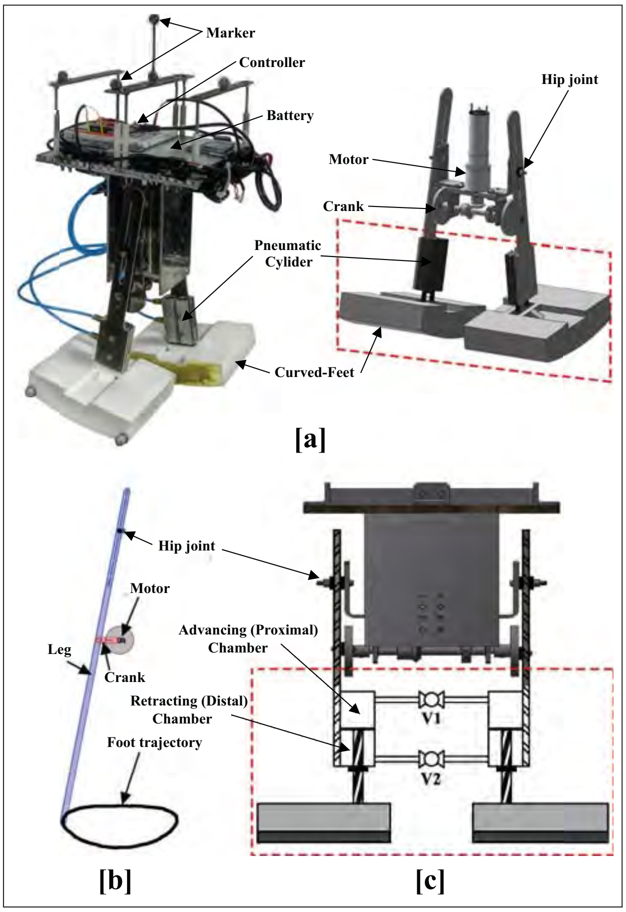


Fig. 1. The developed bipedal robot "PedestriANS". [a] Mechanical structure illustration of the robot. [b] Inverted Slider-Crank mechanism. [c] Valve system diagram of the ANS.

forces against the ground. With these feet, and the symmetrical distribution of the robot's mass, the robot realizes self-balance during locomotion that prevents it from falling down.

B. Actuator Network System ANS

As mentioned earlier, the Actuator Network System (ANS) was proposed in recent researches to improve a robot's adaptability during locomotion [19], [20], [21]. The essence of ANS is the mutual interaction among a network of interconnected actuators; with every pattern connecting these actuators, different body dynamics will emerge.

A simple valve system of two manually actuated hand-valves forms the ANS of our bipedal robot "PedestriANS". It connects the robot's legs as illustrated in figure 1-c. Valve V1 links the advancing chambers (proximal) of the two cylinders together, while valve V2 links the retracting chambers (distal) together. The difference in air pressure between the two chambers of a cylinder affects the net force applied on its piston; therefore, this pressure difference is the reason behind the extension, retraction, and compliance adjustment of a robot's leg. For example, higher pressure in the advancing chamber compared to the retracting chamber will result in an extension of the robot's leg, and vice versa.

The different combinations of open/ close valves are what define the interactive nature between the robot's legs themselves and the environment. If both valves are closed, independent legs will be created with compliance determined by the sealed air pressure inside each cylinder. On the contrary, mutually interconnected legs will be created if both valves are kept open, allowing force transmission between the two legs. As a result of these different connection patterns of the ANS between the robot's legs, the robot can modify its whole body dynamics through its interactions with the environment, providing a wide range of behaviors that could be exploited for better adaptation.

Although the robot has rigid feet that are not compliant themselves, the whole body dynamics and its compliance can be manipulated and adjusted by using the different connection patterns of the ANS.

III. Analyzing the Robot's Behavior at Different Connections of the ANS and on Different Ground Materials

To evaluate the robot's locomotion behavior and investigate its adaptability to various environments, we have conducted our experiments on different ground materials, such as slippery, rigid, and soft ones. Throughout the experiments, we examined how the different connection patterns of the ANS affect the robot's behavior.

A. Connection Patterns

During the conducted experiments, the robot's movement was examined with three different types of legs, as illustrated in figure 2. Under type 1, we set the air pressure inside the cylinders with proper values to get the legs at their half-advanced lengths. Then, we keep both of the valves open to allow energy transfer between the two legs. For example, in this case, 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.

To get compliant legs under type 2, we only pressurize the advancing (proximal) chambers of both cylinders, while keeping the retracting (distal) chambers under atmospheric pressure. After that, we close both of the valves to prevent any direct interaction between the robot's legs, as illustrated in figure 2-b. In this case, the locked air inside the chambers of each actuator will create independent spring-like legs.

Contrary to type 2, in the situation of type 3 legs, we only pressurize the retracting (distal) chambers of both cylinders, while keeping the advancing (proximal) chambers under atmospheric pressure. Consequently, the robot's legs will fully retract to create rigid legs with no interaction between them, as shown in figure 2-c.

B. Procedure and Experimental Settings

To examine how changing the robot's dynamics (through changing the connection patterns of ANS) will affect the stable/ adaptable walking behavior of the robot, experiments were conducted on three different ground materials.

- Ground 1: Carpet on a leveled ground, as shown in figure 3-a; to test the robot's behavior on a rigid ground surface.
- Ground 2: Plastic cardboard, as shown in figure 3-b; to test the robot's behavior on a slippery ground surface.
- Ground 3: Carpet on a sponge, as shown in figure 3-c; to test the robot's behavior on a soft ground surface.

For each type of legs mentioned earlier in this section, ten trials were conducted on each of these three ground materials to investigate the robot's locomotion. After preparing the robot and selecting one of the three legs types, the following procedures are performed during every trial on all ground materials:

1) Run the robot, place it on the ground and guide its movement direction during the first ($0.40 \sim 0.50$ m) to make sure that the robot is moving in a straight path alongside the Z-axis, as demonstrated in figure 4.

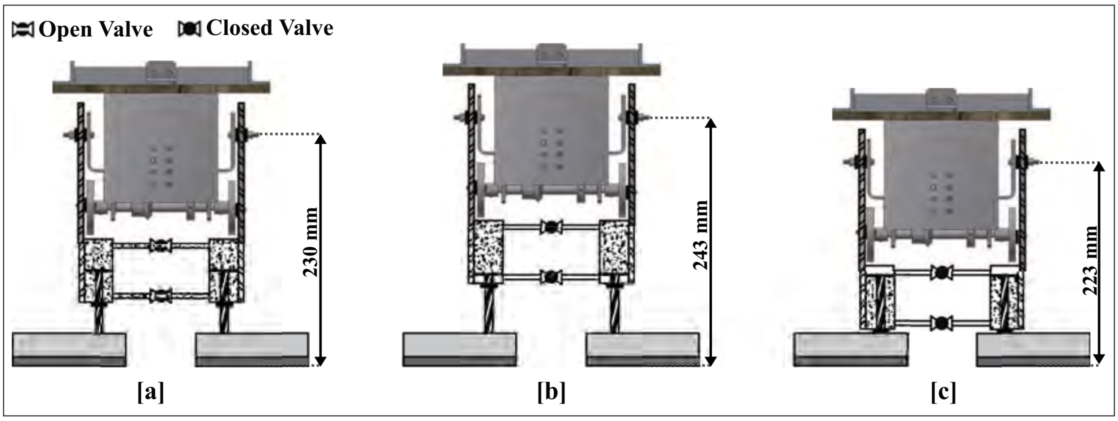


Fig. 2. The applied connection patterns during experiments. [a] Type 1: Mutually connected legs; both cylinders are set at their half-advanced lengths, and the valves are kept open to allow energy transfer between legs. [b] Type 2: Independent compliant legs; both cylinders are fully extended by pressurizing the advancing chambers, and the valves are kept closed to prevent any direct interaction between legs. [c] Type 3: Rigid legs; both cylinders are fully retracted by pressurizing the retracting chambers, and the valves are kept closed to prevent any direct interaction between legs. * Leg length: is the distance from the hip joint of the robot to the bottom of its feet during its initial posture.

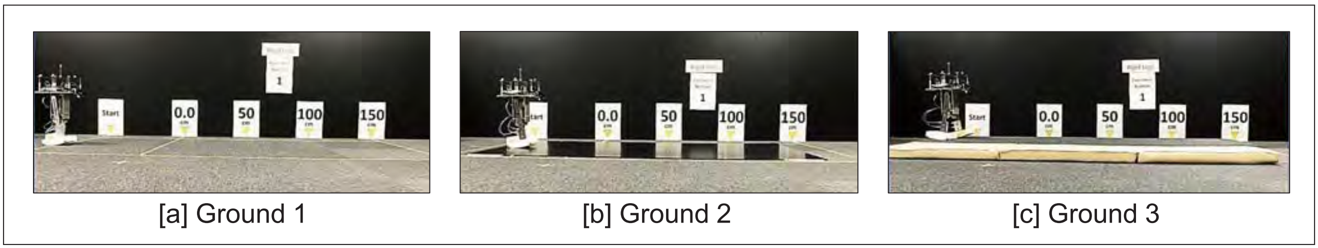


Fig. 3. The ground materials of the conducted experiment. [a] Ground 1: Carpet on a leveled ground. [b] Ground 2: Plastic cardboard. [c] Ground 3: Carpet on a sponge.

2) Release the robot to move by its own for the next (1 $\sim$ 1.5 m).
3) If the robot falls down during a trial before traveling 1 m by its own, the trial is canceled, and one failed trial is registered.
4) Repeat these procedures until completing ten successful trials.

By placing reflective markers on the robot, as shown in figure 1-a, the movement of the robot was analyzed and recorded using a motion tracking system (OptiTrack-V120: TRIO) with a capture frame rate of 120 fps.

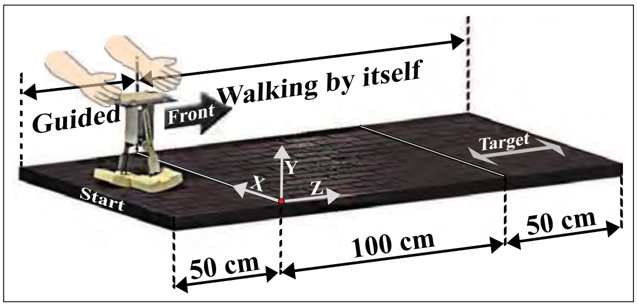


Fig. 4. Schematic diagram of the experimental settings.

C. Results

For each of the conducted trials, the robot's behavior was evaluated by looking into four aspects:

- Direction: whether the robot keeps moving in the same direction or not. This is investigated by observing the walking path of the robot during locomotion.
- Walking style: whether the robot walks in a smooth and gentle way, or have a rough and shaky walking style. This is evaluated by measuring the roll motion, pitch motion, yaw motion, and vertical oscillation of the robot's body, as illustrated in figure 5.
- Stability: whether the robot loses its balance and falls down, or maintains its balance until the end of the trial. The number of trials the robot falls down before reaching the target destination used as an indication for the robot's stability.
- Speed: how fast the robot can reach the target destination. To make sure that the difference in performance does not result from the fact that the three types of legs have effectively different lengths, as shown in figure 2, the speed results are measured after normalizing the lengths of the robot's legs.

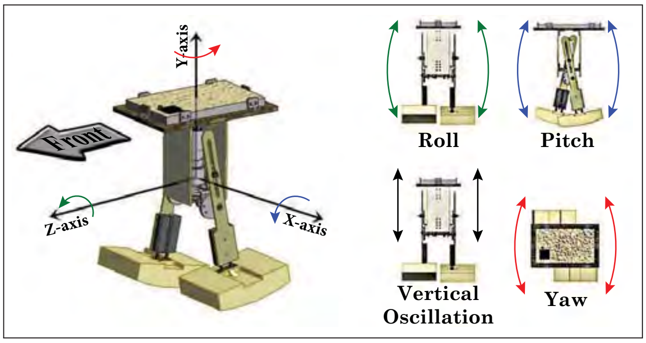


Fig. 5. Illustration diagram of the body motions. *Roll motion: rotation of the robot's body around its front-to-back axis (Z-axis). *Pitch motion: rotation of the robot's body around its side-to-side axis (X-axis). *Yaw motion: rotation of the robot's body around its vertical axis (Y-axis). *Vertical oscillation of the robot's body.

1) Results of the Trials Conducted on Ground 1: By checking the graphs of figure 6, for the experiments conducted on carpet ground material, we can clearly compare the robot's behavior under the different types of legs. With mutually connected legs (type 1) which allows energy transfer between legs during locomotion, the robot maintained its moving direction as it kept walking straight along the z-axis, as shown in the first row of figure 6-a. On the other hand, with compliant legs (type 2) and rigid legs (type 3), once the robot was released to walk by its own without guidance, its walking paths started to diverge into random directions as evident in the figures.

On this ground material, the robot with mutually connected legs did not only have the advantage of moving straight during locomotion, but also exhibited other preferences. The robot walked more gently and smoothly compared to the other types of legs. Referring to the graphs of figure 6-a, counter to the other legs types, the roll motion under type 1 demonstrated periodic oscillation with almost constant amplitude and frequency. In addition to that, the pitch motion, yaw motion, and vertical oscillation of the robot's body had regular oscillations with low amplitudes compared to the other two types of legs, compliant and rigid ones, as illustrated in table 1 of figure 6.

The robot with type 1 legs also showed more stable and adaptable walking behavior on this ground material. As table

2 of figure 6 indicates, the robot with connected legs did not fall down in any of the ten conducted trials. However, the robot fell down one time in case of the compliant legs and six times in case of the rigid legs before completing ten successful trials.

As figure 6-b shows, the robot with type 1 legs was the fastest to reach the target destination among the three types of legs. At the same time, the robot with compliant legs (type 2) and rigid legs (type 3) had slower walking behaviors on this ground material.

2) Results of the Trials Conducted on Ground 2: Plastic Cardboard was selected to examine the robot's locomotion on a slippery ground surface. As can be inferred from table 2 of figure 7, regardless of the connection pattern between the robot's legs, the robot on this ground material has shown a stable walking behavior without falling down during any trial. However, there are still other differences in the robot's behavior among the three types of legs.

While the walking paths of the robot with rigid legs have scattered onto different directions as depicted in figure 7-a, the robot with both connected and compliant legs has kept moving in the same direction even after it was left to walk by itself without guidance.

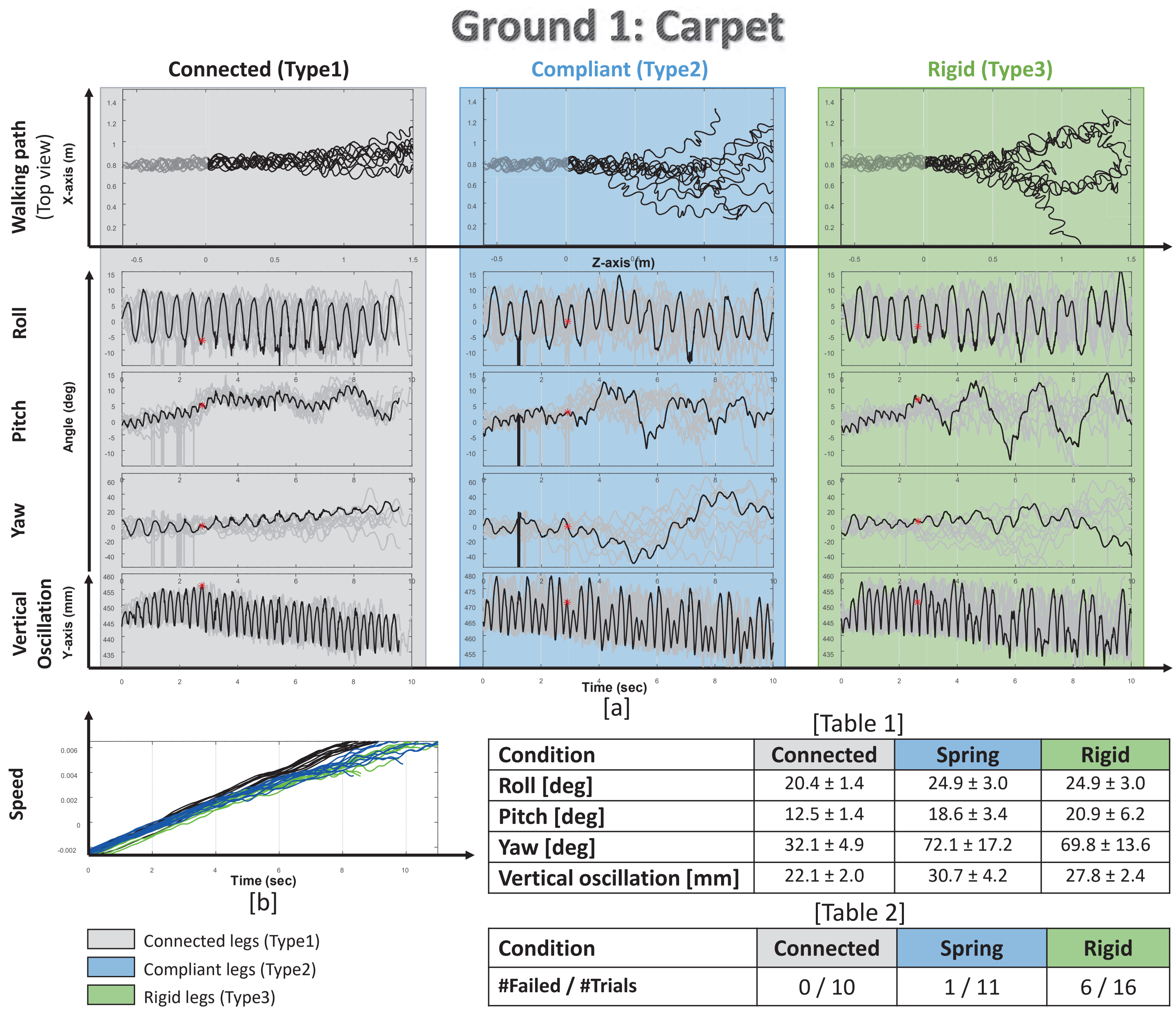
As can be deduced from the motion graphs of roll, pitch, yaw and vertical oscillation of the robot's body; the robot with connected legs (type 1) had relatively better walking style compared to the other two types of legs. For example, from the pitch motion graphs under type 2, the robot kept leaning forward and backward after it was left to walk by itself as shown in figure 9. By taking the difference between its highest and lowest inclination angles, it had an oscillation range of (12.2 $\pm$ 1.5 deg) as demonstrated in table 1 of figure 7. However, it had the lowest oscillation range of (10.4 $\pm$ 2.6 deg) under type 1 legs.

On this ground material, the robot with compliant legs (type 2) was the fastest to reach the target destination among the three types of legs, as shown in figure 7-b. By contrast, the robot with rigid legs (type 3) was the slowest among them.

3) Results of the Trials Conducted on Ground 3: The trials conducted on a sponge material were to examine the robot's locomotion on a soft ground surface. By referring to the walking paths of figure 8-a, it seems that the robot on this ground material managed to maintain its walking direction by moving straight along the Z-axis regardless of the selected connection pattern. However, other differences still can be observed regarding the robot's stability, speed, and walking style.

It is evident from the motion graphs of the roll, pitch, yaw, and vertical oscillation of the robot's body that the robot with rigid legs had the shakiest walking behavior. As table 1 of figure 8 shows, it had the highest and most varying range of oscillation amplitudes of all motions compared to the other two types of legs. For example, from the graphs of pitch motion, under this type of legs, the robot's body kept leaning forward and backward with a high oscillation range of (19.4 $\pm$ 3.7 deg) compared to (10.9 $\pm$ 2.0 deg) and (14.9 $\pm$ 2.7 deg) of type 1 and type 2 legs respectively. By contrast, as on the other ground materials, the robot with type 1 legs seemed to have the smoothest "most gentle" walking behavior. It showed the lowest range of oscillation amplitudes in all of the roll, pitch, yaw, and vertical oscillation of the robot's body as depicted in table 1.

From figure 8-b, the robot with rigid legs (type 3) still had the slowest gait speed to reach the target destination. However, this time, it exhibited the most stable behavior as table 2 of figure 8 shows. The rate in which the robot fell down before reaching the target destination was the smallest (6 / 11) compared to the other two types of legs, connected and compliant legs, which had the rates of (8 / 11) and (10 / 10) respectively.



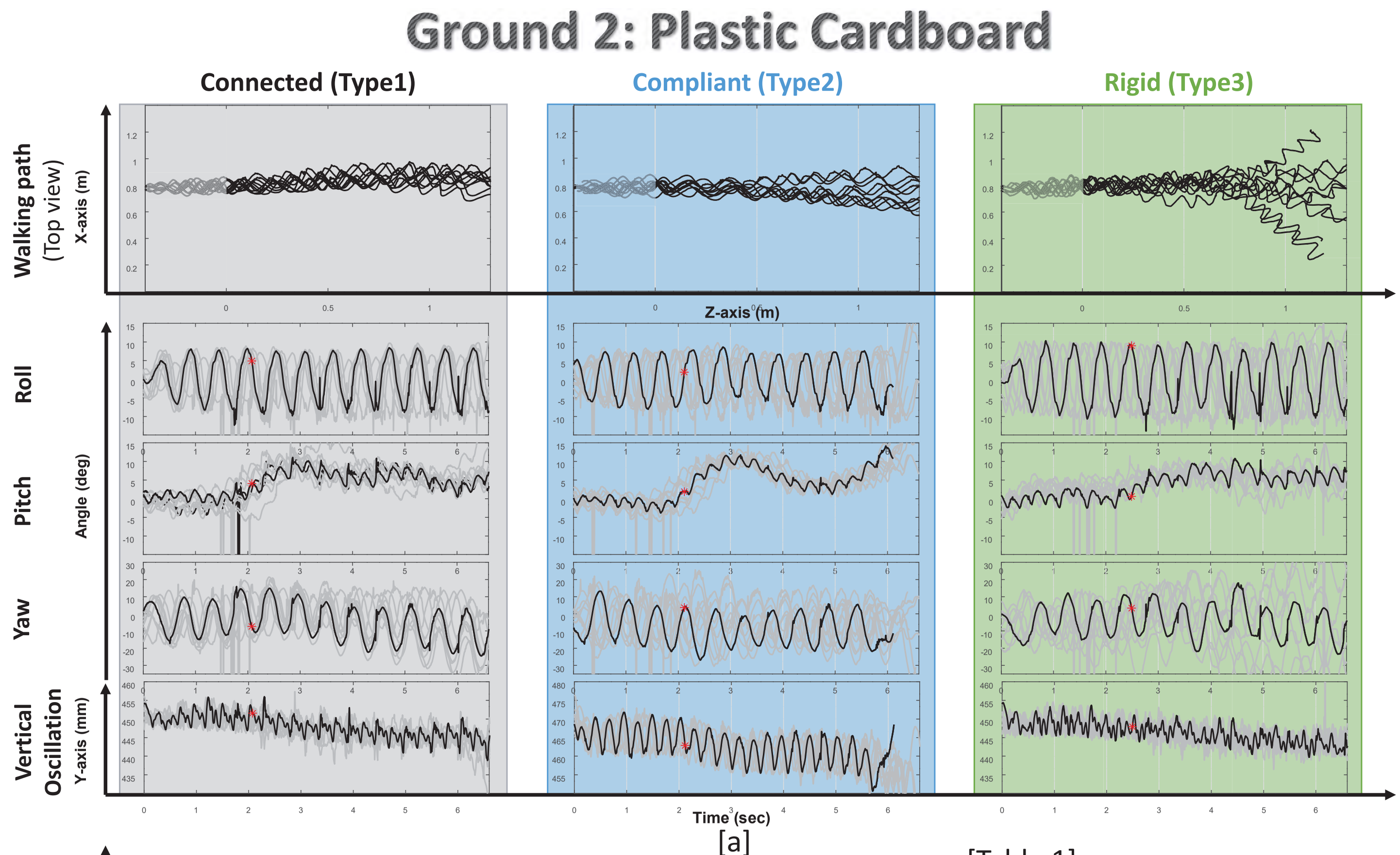
[Table 1]

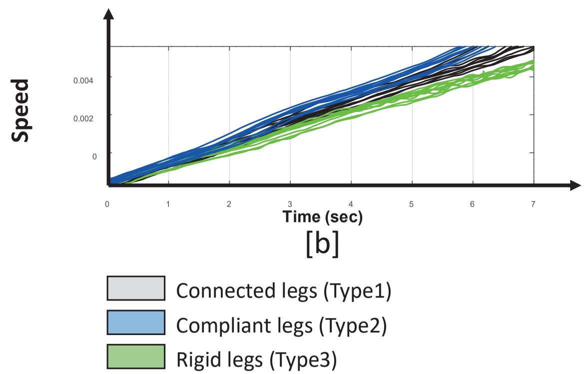
Condition	Connected	Spring	Rigid
Roll [deg]	20.4 ± 1.4	24.9 ± 3.0	24.9 ± 3.0
Pitch [deg]	12.5 ± 1.4	18.6 ± 3.4	20.9 ± 6.2
Yaw [deg]	32.1 ± 4.9	72.1 ± 17.2	69.8 ± 13.6
Vertical oscillation [mm]	22.1 ± 2.0	30.7 ± 4.2	27.8 ± 2.4

[Table 2]

Condition	Connected	Spring	Rigid
#Failed / #Trials	0 / 10	1 / 11	6 / 16

Fig. 6. Results of the conducted experiment on a carpet ground material. [a] Graphs of the Roll, Pitch, Yaw and Vertical oscillation of the robot's body under the three types of legs. The faded part at the beginning of walking path graphs represents the guided period of the robot. The highlighted black lines represent a typical behavior among the ten conducted trials under each type of legs. "*" Indicates the end of the guided period. [b] Comparison of the robot speed under the three types of legs. The vertical axis of figure [b] is an indication of the traveled distance after normalizing the lengths of the robot's legs. [Table 1] The average range (difference between the highest and lowest values) of the Roll, Pitch, Yaw motions [deg] ± S.D, and the Vertical oscillation of the robot's body [mm] ± S.D. [Table 2] The number of trials the robot fell down before reaching the target destination.





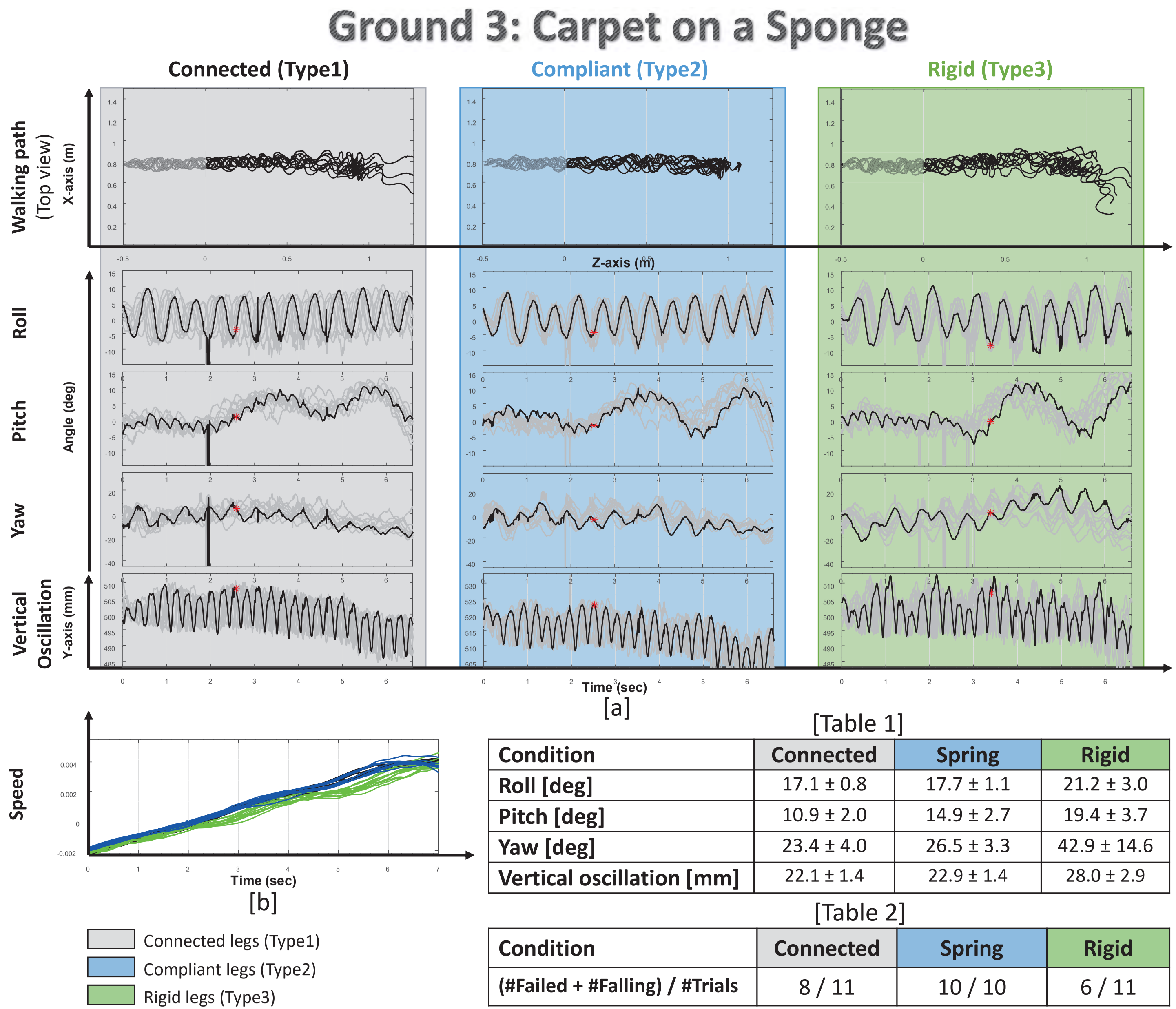
[Table 1]

Condition	Connected	Spring	Rigid
Roll [deg]	18.5 ± 1.2	17.6 ± 0.7	23.6 ± 2.9
Pitch [deg]	10.4 ± 2.6	12.2 ± 1.5	11.2 ± 2.7
Yaw [deg]	41.9 ± 9.3	37.3 ± 4.3	67.7 ± 20.7
Vertical oscillation [mm]	13.0 ± 1.9	18.2 ± 2.2	13.1 ± 1.3

[Table 2]

Condition	Connected	Spring	Rigid
#Failed / #Trials	0 / 10	0 / 10	0 / 10

Fig. 7. Results of the conducted experiment on a plastic cardboard ground material. [a] Graphs of the Roll, Pitch, Yaw and Vertical oscillation of the robot's body under the three types of legs. The faded part at the beginning of walking path graphs represents the guided period of the robot. The highlighted black lines represent a typical behavior among the ten conducted trials under each type of legs. "*" Indicates the end of the guided period. [b] Comparison of the robot speed under the three types of legs. The vertical axis of figure [b] is an indication of the traveled distance after normalizing the lengths of the robot's legs. [Table 1] The average range (difference between the highest and lowest values) of the Roll, Pitch, Yaw motions [deg] $\pm$ S.D, and the Vertical oscillation of the robots body [mm] $\pm$ S.D. [Table 2] The number of trials the robot fell down before reaching the target destination.



[Table 1]

Condition	Connected	Spring	Rigid
Roll [deg]	17.1 ± 0.8	17.7 ± 1.1	21.2 ± 3.0
Pitch [deg]	10.9 ± 2.0	14.9 ± 2.7	19.4 ± 3.7
Yaw [deg]	23.4 ± 4.0	26.5 ± 3.3	42.9 ± 14.6
Vertical oscillation [mm]	22.1 ± 1.4	22.9 ± 1.4	28.0 ± 2.9

[Table 2]

Condition	Connected	Spring	Rigid
(#Failed + #Falling) / #Trials	8 / 11	10 / 10	6 / 11

Fig. 8. Results of the conducted experiment on a sponge ground material. [a] Graphs of the Roll, Pitch, Yaw and Vertical oscillation of the robot's body under the three types of legs. The faded part at the beginning of walking path graphs represents the guided period of the robot. The highlighted black lines represent a typical behavior among the ten conducted trials under each type of legs. "*" Indicates the end of the guided period. [b] Comparison of the robot speed under the three types of legs. The vertical axis of figure [b] is an indication of the traveled distance after normalizing the lengths of the robot's legs. [Table 1] The average range (difference between the highest and lowest values) of the Roll, Pitch, Yaw motions [deg] $\pm$ S.D, and the Vertical oscillation of the robot's body [mm] $\pm$ S.D. [Table 2] The number of trials the robot fell down before reaching the upper limit of the target destination.

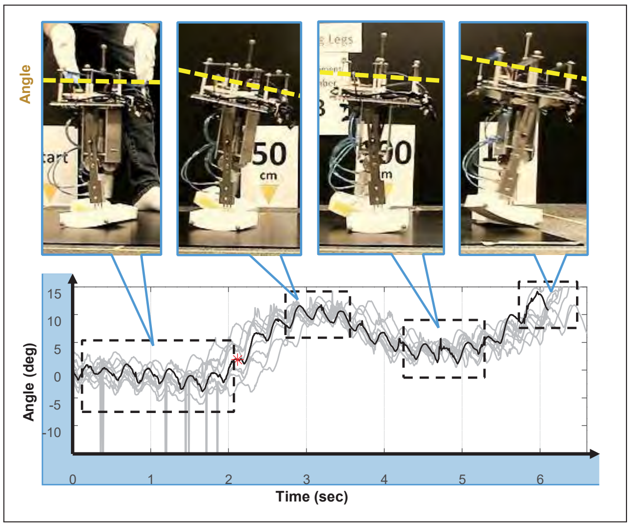


Fig. 9. The corresponding body postures of the robot to its pitch angle oscillation during locomotion on Ground 2 with type 2 legs.

IV. Supplementary Experiment: Switching Connection Pattern During Locomotion to Enhance the Robot's Behavior

So far, the conducted experiment examined the pros and cons of each connection pattern separately; where during each trial, a single type of legs was tested. However, by referring to table I, which summarizes the results of all experiments, the robot's demands for a certain connection pattern to produce better behavior differ based on the surrounding environment. For example, the type of legs that showed the worst behavior on carpet ground material, it was the same type of legs that showed the most stable behavior on sponge ground material. Therefore, for this robot to operate on an actual unstructured environment, it should be enabled to switch between the different connection patterns during locomotion to better suit the given situation.

TABLE I

Summary results of section III-C.

Ground	Connection	Direction	Walking style	Speed	Stability
Carpet	Type1	+	+	+	+
	Type2	-	0	-	0
	Type3	-	-	-	-
Plastic cardboard	Type1	+	+	0	+
	Type2	+	0	+	+
	Type3	-	-	-	+
Sponge	Type1	+	+	+	0
	Type2	+	0	+	-
	Type3	+	-	-	+

"+" Represents best behavior (maintains direction, gentle walking style, fastest, and most stable). "-" Represents worst behavior (changes direction, rough walking style, slowest, and least stable). "0" Represents intermediate behavior (between + and -).

A. *Procedure and Experimental Settings*

For the purpose of testing how switching between different connection patterns will enhance the robot's behavior, here, in this supplementary experiment, we have updated the robot structure as shown in figure 10-a. The manually actuated valves were replaced with electronically actuated ones. A tank was also mounted on the robot's body to supply the actuator network system with the required air pressure.

The experiment was conducted on a carpet ground material as demonstrated in figure 11. To examine the effect of switching between connection patterns during the robot's locomotion, the experiment starts with the robot having rigid legs, which previously showed unstable behavior on this ground material. The robot then automatically switches its connection to mutually connected legs, which already showed a stable walking behavior on this ground material.

Figure 10-b shows the updated actuator network system. Before starting the experiment, the lower chambers of both cylinders are pressurized through inlet 1. Afterwards, both valves V3 and V4 are closed to create rigid legs. While keeping V2 closed, the tank also gets pressurized through inlet 2. The robot will switch to connected legs during locomotion by opening both V1 and V2 valves.

The type of connected legs in this experiment slightly differs from the previously used connected legs. The former type of connected legs, shown in figure 2-a, connects the upper chambers of both cylinders, as well as the lower chambers. However, here, the upper chambers of both cylinders are connected while the lower chambers are not. Similar to the former type, once a robot's leg hits the ground and enters the stance phase, it will fully retract; causing an expansion of the other leg. However, the difference here, once a robot's leg enters the swing phase; it will directly return to its equilibrium length, without the need to wait for the other leg to enter the stance phase to get expanded.

For this experiment, five trials with a duration of twelve seconds each were conducted. During each trial, the robot starts walking with rigid legs. To reduce the probability of the robot from falling down during the rigid legs period, the duration under this condition is set to be only four

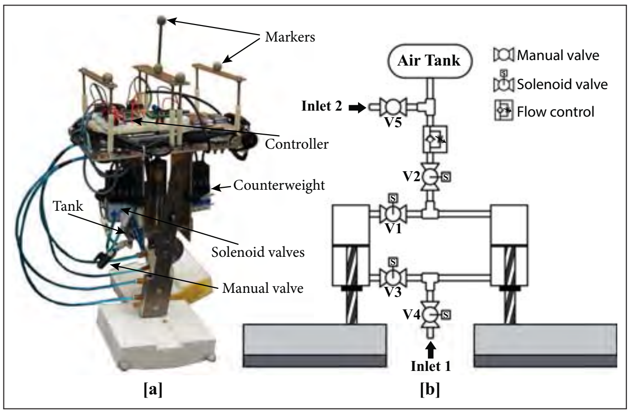


Fig. 10. [a] The updated structure of "PedestriANS". [b] The updated ANS.

Fig. 11. Experimental environment.

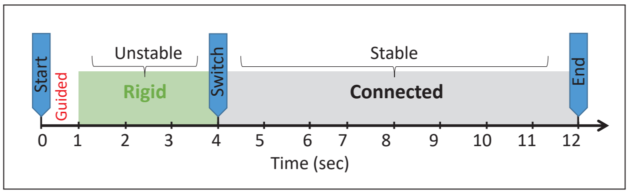


Fig. 12. Experimental design: Switching connection pattern during locomotion.

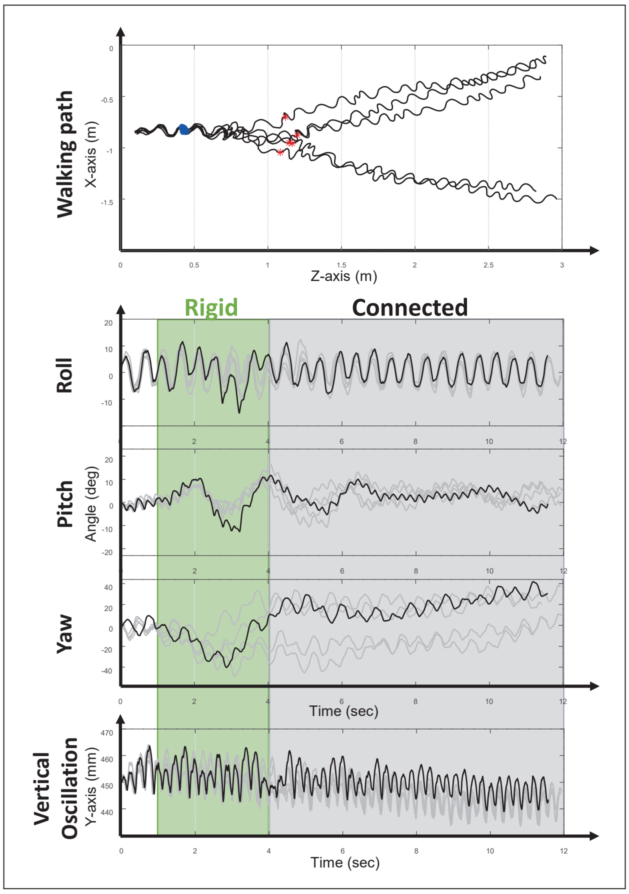


Fig. 13. Results of the supplementary experiments. From top to bottom, the graphs are walking path, roll motion, pitch motion, yaw motion, and vertical oscillation of the robot's body. The green-shaded part (from 1 sec to 4 sec) represents the duration of the robot with rigid legs. The gray-shaded part (from 4 sec to 12 sec) represents the duration of the robot with mutually connected legs. The highlighted black lines represent one of the five conducted trials. "•" Indicates the end of the guided period. "*" Indicates the moment of switching.

seconds. During the first second, the robot is guided. For the remaining three seconds, the robot is unguided. The robot then automatically switches to mutually connected legs for the remaining eight seconds As demonstrated in figure 12 .

B. Results

Similar to the previous experiment, the walking path, roll motion, pitch motion, yaw motion, and vertical oscillation of the robot's body were measured to evaluate the robot's behavior. By looking to the graphs of figure 13, we can notice the significant improvements that happened to the robot's gait after switching to connected legs.

The roll motion during the rigid legs period was oscillating with high range and variable amplitudes. However, once the robot switched to the connected legs as the figure shows, it started recovering from this unstable behavior to end up with a periodic oscillation that has lower and constant amplitudes.

The same thing can also be seen from the pitch motion graphs. During the rigid legs period, the robot was almost falling due to the high range of angle oscillation in the forward and backward directions. It's worth mentioning here that even with this short period for this part to prevent the robot from falling down before switching to the connected legs; almost 50 % (4 / 9) of the conducted trials the robot fell down and didn't make it to the connected legs. For the rest of the trials in which the robot made it to the connected legs without falling down; the robot directly started correcting its behavior gradually until it maintained a stable behavior with an upright body posture.

From the yaw motion graphs, the unstable behavior of the robot during the rigid legs period is represented by the continuous changing of the walking direction. However, once the robot switched to the mutually connected legs, it started maintaining its direction. This behavior of the yaw motion reflects directly to what we see in the graphs of the walking path. The robot during the rigid legs period deviated into random moving directions. However, the robot maintained that direction, and kept moving straight after switching to the connected legs.

The changes happened to the vertical oscillation of the robot's body after switching to the connected legs may have the least noticeable improvement. However, with a closer look to the graphs, we can notice how at the end of all trials the robot achieved lower and constant oscillation amplitudes compared to the higher and variable oscillations at the beginning of the trials.

V. Discussion

For the conducted experiments on each of the ground materials, the robot's walking behavior has changed by changing the interaction between the actuators of the ANS.

Based on these differences in the robot's walking behavior, as the results show, its demands for a certain connection pattern differ based on the given situation. For example, the connection pattern that better suits a certain ground material, it does not necessarily suit other ground materials, and what is bad for some ground materials, it might be the best for others. Exploiting these various dynamics is the way to enable the robot from realizing adaptability to any given situation, and to develop an efficient gait pattern through all locomotion phases.

Each of the robot's feet has considerable weight; thus, a leg expansion during its swinging phase, in the case of types 1 and 2, directly affects the COM of the robot's body. In light of this, the difference in performance between mutually connected legs (type 1) and independent compliant legs (type 2) are not due to a mere difference in compliance. But also the time and manner of expansion affect the performance too. The expansion of a swinging leg, in case of type 1, depends on the stance leg since both legs are mutually connected. However, the expansion is independent of the stance leg in case of type 2. Therefore, the time for a swinging leg to get fully extended is different, and consequently has a different effect on positioning the COM of the robot, which in turn produces different body dynamics.

By looking at the vertical oscillation results of all experiments, there is a noticeable gradual decrease in the robot's height with time. The reasons behind this behavior are threefold. First, during the guided period, the robot's body is partially supported by the operator's hands; therefore, once the robot is left to walk by itself, its height slightly decreased as shown in the graphs. Second, by knowing that the height of the robot is being measured from the ground to the highest reflective marker placed on its body, its height will get directly affected by both roll and pitch motions. As leaning towards any direction (front, back, right, or left) during the robot's locomotion will result in a decrease in its height. Therefore, the vertical oscillation kept decreasing during some experiments in response to the increasing oscillation of either roll motion, pitch motion, or a combination of both. The third and most important point, the used device for capturing these data, OptiTrack-V120: TRIO, uses a calibration square to define the ground plane. However, there is a difference between the defined plane and the actual floor surface, and they do not perfectly match. Although the difference between the two planes is very small and negligible, it is still visible in the graphs due to the used small scale of the Y-axis (millimeter). To measure this difference, we can refer to the trials conducted on Ground 2 (plastic cardboard) with rigid legs (type 3); because in this case the robot has a fixed leg length and never changes its height during locomotion. The difference in height between the beginning and end of the trial is 6 mm, and the robot traveled a distance of 1.9 m. Therefore, it is suggested that the angle between the defined horizontal plane of the sensor and the actual floor surface is at most $0.18°$. A similar inclination line can be found on other ground materials as well.

Having different length for each of the three types of legs could affect the walking speed of the robot. To rule this out for the results of the conducted experiments, the speed graphs were made after normalizing the lengths of the robot's legs. However, even after this normalization, the graphs still show speed results that are independent of the leg's length. For example, the robot's walking speed with type 2 legs (longest legs) compared to type 1 legs was slower on Ground 1 as shown in figure 6-b, faster on Ground 2 as shown in figure 7-b, and similar on Ground 3 as shown in figure 8-b. Also, the speed results of the robot under type 2 and type 3 legs on Ground 1 is another example proving that the main factors affected the robot's behavior were the selected connection pattern between the robot's legs (mutually interconnected, independently compliant, or stiff), and the environment in which the robot is operating. The robot had relatively similar speeds, as figure 6-b shows, although type 2 has the longest legs while type 3 has the shortest ones. There are many aspects that need to be looked at to understand the reasons behind these differences in the robot speed. The locomotion speed of a robot is influenced by many factors such as length of legs [23], [24], rotational slip that is caused by the yaw moment on the stance leg [25], elasticity of legs [26], the impact force between robot's feet and the ground [27], etc. Therefore, studying the effects of applying different connection patterns of the ANS on these factors would be an interesting area of study to be addressed in future work.

Furthermore, an additional experiment was also conducted on Ground 1 to exclude the effect of different legs lengths. The purpose of the experiment was to test the robot's behavior with Long rigid legs, then compare its performance with type 2 legs (similar length, different compliance). Despite having the same length for its rigid and compliant legs, the robot's behavior was still significantly different. The robot with rigid legs did not manage to complete any of the trials successfully as it kept falling before reaching the target destination. However, the robot with compliant legs, on the other hand, had much more stable behavior on the same ground material. It fell only one time out of the 11 conducted trials, as table 2 of figure 6 shows. Therefore, this clear difference in performance between the two types of legs is undoubtedly due to their different compliance as they both had the same length.

"PedestriANS" have shown an improvement in its behavior by changing the way its legs are interacting with each other. However, as mentioned earlier, the efficient, stable, and adaptive walking behavior of humans is not limited to the interaction between the two legs, but also a result of the interactions among the different parts of their bodies. Therefore, by expanding the ANS to include more parts of the robot's body (which will be addressed in the future work), further enhancements will be realized in its behavior. This will increase the possible morphological changes, which in turn reflects on the robot's adaptability.

From the supplementary experiment, the robot managed to retrieve its stable behavior after switching to a different connection pattern during locomotion. However, with the current ANS, due to the limited pressurized air inside the tank, automatic switching between two different connection patterns can only be done one time per trial. Therefore, to solve this problem in the future work, an air pump will be installed on the robot's body.

In this study, testing the robot's behavior under three types of legs, and on three different ground materials is just an example to show that the robot with ANS can adjust its whole body dynamics to adapt to a given environment. However, applications are not only restricted to these types of legs nor these ground materials. Moreover, although the results of the conducted experiments have only tackled the robot's behaviors in terms of the walking style, stability, speed, and moving direction, possible improvements could be much more than that.

Thus, the first step in the future work is to upgrade the robot's design. The upgrade will include expanding the ANS to cover more parts of the robot's body, installing an air pump to allow continuous ability of switching between the different connection patterns, and enabling the robot from autonomously choosing an adequate connection pattern to suit the given situation. The second step is to conduct experiments on terrains with various geometric properties (e.g., flat, sloped, rough, etc.) and different physical properties (e.g., slippery, hard, soft, etc.). The third step is to evaluate the robot's performance and its adaptability by checking its maneuverability, obstacles avoidance capability, and its ability to recover stable behaviors after stumbling over sudden obstacles.

VI. Conclusion

This paper presents the development of a bipedal robot with adaptive morphology, called PedestriANS. By using an Actuator Network System (ANS) coupled with the robot's body, the robot is able to adjust the physical characteristics of its legs (compliance and stiffness), as well as changing the way its legs are interacting with each other's and the environment.

To test our hypothesis that a robot performance on varying environments cannot be at its best with a single body morphology, but it needs to respectively change its whole body dynamics for better adaptation, two experiments have been conducted, main and supplementary experiments. The purpose of the main experiment is to examine how effective is changing the robot's morphology on its behavior. Therefore, trials have been conducted on three different ground materials (rigid, slippery, and soft), and under three different connection patterns between the robot's legs (rigid legs, compliant legs, and mutually connected legs). The robot's behavior was evaluated by taking into consideration four aspects, the waking style of the robot, stability, moving direction, and speed. With every connection pattern on each of the ground materials, as the results showed, the robot generated various dynamics and locomotion behaviors due to the different interactions between the robot's legs themselves, and the environment. These results came to support our hypothesis; the robot required different connection patterns between its legs to show better performances based on the given ground material. For example, a connection pattern that produced stable behavior on a certain ground material, showed unstable behavior on other ground materials, and vice versa.

For the supplementary experiment, the robot's ANS was updated. The robot now is able to switch between the different connection patterns during locomotion. The purpose of this experiment is to put the idea of implementing ANS to the test, and check whether it will enhance the robot's performance during locomotion or not. For this purpose, we used the results obtained from the main experiment. For example, on a rigid ground material, the robot with rigid legs showed unstable behavior; however, on the same ground material, the robot with mutually connected legs established stable behavior. Therefore, by using the same ground material for the supplementary experiment, the robot started its locomotion with rigid legs for a few seconds. Then, it automatically switched to mutually connected legs. Similar to what it was expected; the robot managed to rectify its behavior during locomotion. The robot started its locomotion with unstable behavior. However, after switching its connection pattern, the robot directly started correcting its locomotion to end up with stable behavior.

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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. Aoi, P. Manoonpong, Y. Ambe, F. Matsuno, & F. Wrgtter, Adaptive Control Strategies for Interlimb Coordination in Legged Robots: A Review. Frontiers in Neurorobotics, 11, 39, 2017.

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

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

[6] K. Kaneko, F. Kanehiro, M. Morisawa, K. Akachi, G. Miyamori, A. Hayashi, & N. Kanehira, Humanoid robot HRP-4 Humanoid robotics platform with lightweight and slim body. Proceedings of the 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS2011), 2011.

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

[8] S. Mintchev, & D. Floreano, Adaptive morphology: A design principle for multimodal and multifunctional robots. IEEE Robotics & Automation Magazine, 23, 3, 4254, 2016.

[9] R. Pfeifer, M. Lungarella, & F. Iida, Self-organization, embodiment, and biologically inspired robotics. Science, 318, 5853, 10881093, 2007.

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

[11] 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.

[12] 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.

[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] R. V. Ham, S. Thomas, B. Vanderborght, K. Hollander, & D. Lefeber, Compliant actuator designs: Review of actuators with passive adjustable compliance/controllable stiffness for robotic applications. IEEE Robotics and Automation Magazine, 16,3,8194, 2009.

[15] 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.

[16] M. Wisse. Essentials of Dynamic Walking : Analysis and Design of Two- Legged Robots. PhD thesis, Technische Universiteit Delft, 2004.

[17] 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.

[18] 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.

[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. Ahmad, Y. Nakata, Y. Nakamura, & H. Ishiguro, A Bipedal Robot with an Energy Transfer Mechanism between Legs: A Pilot Study. IEEE International Conference on Robotics and Biomimetics (ROBIO) 2018, Kuala Lumpur, Malaysia.

[21] H. Ahmad, Y. Nakata, Y. Nakamura, & H. Ishiguro, A study on energy transfer among limbs in a legged robot locomotion. Adaptive Behavior, 26, 6, 309-321, 2018.

[22] V. S. Karelin, On the synthesis of the inverted slider-crank mechanisms for approximate straight-line motion. Mechanism and Machine Theory, 21, I, 13-18, 1986.

[23] R. Ringrose, Self-stabilizing running. Proceedings of International Conference on Robotics and Automation IEEE, 1, 487-493, 1997.

[24] D. Webb, Maximum walking speed and lower limb length in hominids. American Journal of Physical Anthropology.101,4,515-525, 1996.

[25] F. Zhao, & J. Gao, Anti-Slip Gait Planning for a Humanoid Robot in Fast Walking. Applied Sciences. 9, 13, 2657, 2019.

[26] J.C. Dean, & A.D. Kuo. Elastic coupling of limb joints enables faster bipedal walking. Journal of the Royal Society Interface. 6, 35, 561573, 2009.

[27] M. Luneckas, T. Luneckas, & D. Udris. Leg placement algorithm for foot impact force minimization. International Journal of Advanced Robotic Systems. 15, 1, 2018.