Comparing Arc-shaped Feet and Rigid Ankles with Flat Feet and Compliant Ankles for a Dynamic Walker

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In this paper we show that exchanging curved feet and rigid ankles by flat feet and compliant ankles improves the range of gait parameters for a bipedal dynamic walker. The new lower legs were designed such that they fit to the old set-up, allowing for a direct and quantitative comparison. The dynamic walking robot RunBot, controlled by an reflexive neural network, uses only few sensors for generating its stable gait. The results show that flat feet and compliant ankles extend RunBot's parameter range especially to more leaning back postures. They also allow the robot to stably walk over obstacles with low height.

Keywords: Dynamic Walking; Biped; Neural Control.

1. Introduction

Passive dynamic walking is assumed to be a good approach towards energy efficient human-like walking. The term was introduced by McGeer in 1990,[1] and describes dynamic walking that uses no actuation of the joints of the walking machine. The concept of exploiting the walking machine's biomechanics to produce a stable gait that does not consume a high amount of energy has been succesfully adopted to dynamic walkers with actuated joints since then and is nowadays a common design.[2]

To aid the dynamic walking machines in rolling forward and keeping their momentum, arc shaped feet that are rigidly attached to the lower legs are commonly used. Although this leads to more human-like gaits, neither arc-shaped feet nor ankles seem very human-like. Human ankles show compliant

behavior during walking and running. To mimic this, more recent designs rather use flat feet and torsion springs for compliant ankles. Another advantage in this design is that the feet usually touch the ground with their complete flat surface. Arc-shaped feet touch the ground only in one point (or in one line for 3D-models). This makes them more sensitive to disturbances on the surface. Exchanging arced feet on existing dynamic walkers by flat feet and compliant ankles can lead to stable gaits.[3]
In this study, the range of stable parameters for both common set-ups, flat feet and arc-shaped feet, are compared for the bipedal walker RunBot.[4,5] A new pair of lower legs with flat feet and compliant ankles has been built for it. The old lower legs (arc-shaped feet, rigid ankles) can now easily be replaced by the new ones. For further comparison of stability, the success rate of overcoming obstacles with different heights is also investigated.

2. Methods

Biomechanical Set-up

RunBot is a bipedal dynamic walker. It currently has two different biomechanical set-ups. The first classical one has arc-shaped feet and rigid ankles.[4–6] In the second setup lower legs with flat feet and compliant ankles replace the lower legs of the classical setup. The first variation is referred to as the old setup, the second one as the new setup.
The robot has two hip and knee joints, driven by a servomotor each. The

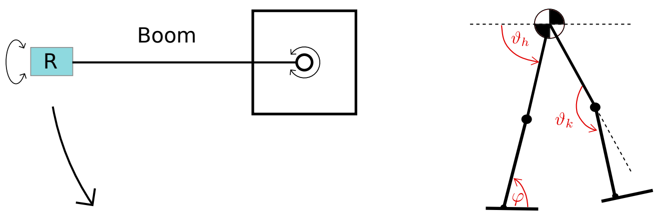


Figure 1. *Left.* Top-view of the set-up. A boom connects RunBot to a central fixation point. *Right.* Angles between RunBot's limbs.

servomotors' built-in control circuits are disconnected, while their potentiometers are used to measure the joints' angles.
Beside the potentiometers, RunBot has two ground contact sensors. The ground contact sensors and the angle sensors (potentiometers) provide the only feedback to generate the locomotion.

RunBot is connected to a boom that stabilizes it sagitally. It cannot

fall sidewards. In the following the term 'stable gait' means the gait allows RunBot to walk without falling backwards or forwards. The boom restricts RunBots trajectory to a circle. Besides that, the boom is used to lead wires to RunBot. The central anchor of the boom has a slip ring capsule inserted, so that no wire can produce undesired forces due to torsion from RunBot's circular movement.
RunBot is controlled with a Linux computer that communicates with an USB-DUX (a data aquisition unit). The USB-DUX' output is partly amplified.

Main differences between old (arc-shaped feet, rigid ankles) and new design (flat feet, compliant ankles) are depicted in the following.

Arc-shaped feet and rigid ankles

Using arc-shaped feet and rigid ankles, RunBot is 23.2 cm tall from foot to hip joint. The arc-shaped feet aid the robot in 'rolling' forward and keeping its momentum.
The ground contact sensor in this design consists of two conducting areas that get short-circuited when the inner part of a lower leg moves up, that is, when the right or left foot hits the ground or an obstacle. This concept leads to an undesired initial bouncing in the signal during numerous steps. An excerpt of 6 steps of the signal can be seen in fig. 2 (right).

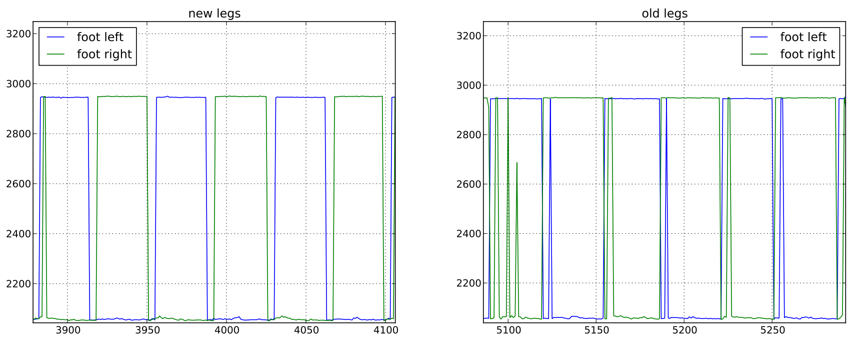
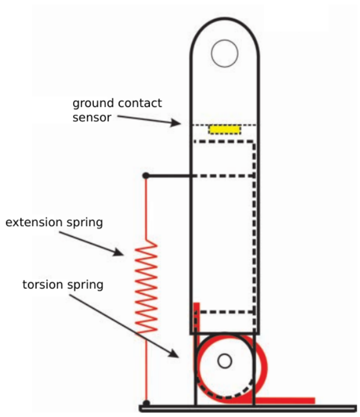


Figure 2. Ground contact sensor signals for roughly 6 steps, one run with new legs and one with old legs. Data was recorded during previous experiments. Showing the sensor signals on the y-axis, time steps on x-axis. Note that the sensor signal is pulled down if the sensor is triggered; a value of around 2050 meaning that the respective foot feels ground contact.



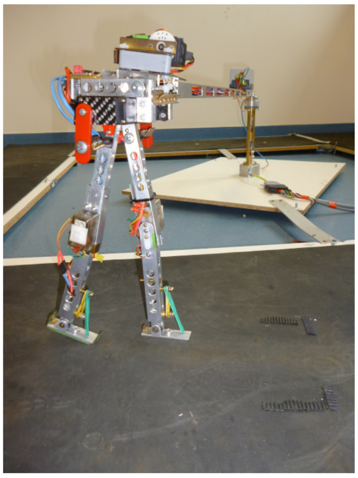


Figure 3. *Left.* Sketch of the new lower leg design with flat foot and compliant ankle. Leg consists of inner and outer part, dashed lines indicate edges of inner part. Figure is modified from [7]. *Right.* Picture of RunBot with new legs.

Using the new lower legs, RunBot is 0.5 cm smaller (the height is 22.7 cm from foot to hip joint). Whilst arc-shaped feet only touch the ground at one point, flat feet usually touch it with their entire surface. Along with passive ankle joints, one would expect more robustness from this design. With this new design we use a micro switch as its ground contact sensor[a]. Since the switches have a certain distance where they trigger, they mechanically filter out most of the initial bouncing that can be observed in the old lower legs. The old and new ground contact sensor signals can be compared in figure 2. For more details about the new legs' design see [7].

Neural Controller

RunBot's controller was designed following the classical subsumption architecture,[8,9] starting out with a low layer of control (reflexive neural controller/spinal reflex level),[4] and adding a higher layer of control (adaptive neural controller/postural reflex level) afterwards.[5]

[a]Cherry Switches Subminiatur-Schalter DG 125 V/AC DG13-B3LA

As the name suggests, the reflexive neural controller utilizes reflex based methods[10] to control RunBot's gait. The network is shown in figure 4. Its neurons are modelled as non-spiking neurons with standard sigmoid transfer functions. The motor neurons have mono synaptic connections, they produce a linear output which is sent unaltered to the motors. The network does not use any explicit gait calculations or trajectory planning; it rather uses the sensory feedback to invoke output of the motor neurons which directly drive the motors at the joints. It creates a human-like movement of the legs by reacting to the sensor signals, e.g. ground contact at the left foot (GL) induces the right leg to swing forward, the swinging is stopped when the right hip reaches the extensor sensors' (ES) thresholds. The right leg should be fully extended by then and ready to function as stance leg during the next step. Note that the angle sensor neurons' thresholds only roughly limit the legs' movements (the actual angles ϑ as shown in figure 1, *right*, can exceed ES and FS thresholds θ).

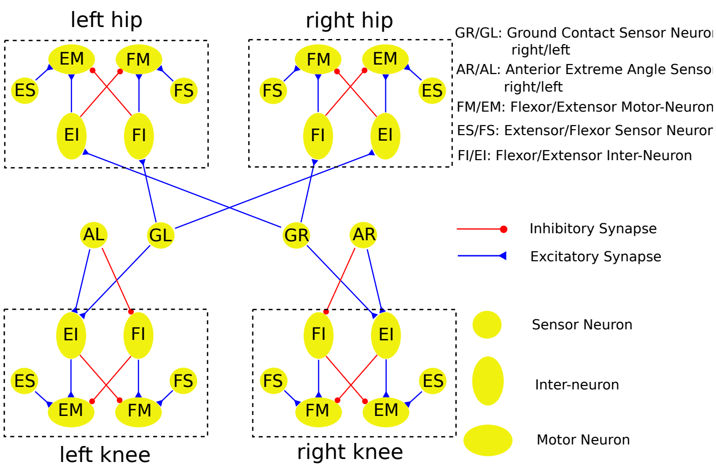


Figure 4. Model of the reflexive neural controller. The stability of the controller is shown in [5,6] and can also be investigated using an analytical approach as presented in [11].

3. Experiments and Results

In the experiments the parameter range of stable gaits for both set-ups was explored. Only the values for $\theta_{h,max}$ and $\theta_{h,min}$ were changed, while all the other parameters stayed fixed.

The values of $\theta_{h,min}$ were changed in two degree steps . For each $\theta_{h,min}$, plausible values of $\theta_{h,max}$ were scanned through in two degree steps. Sometimes one degree steps were used here, if no stable values were found initially but the gaits seemed stable enough to encourage a closer look. A pair of parameters ($\theta_{h,min}$,$\theta_{h,max}$) was classified as successful if RunBot could walk at least half of the circular path. The resulting parameter ranges are plotted in figure 5.

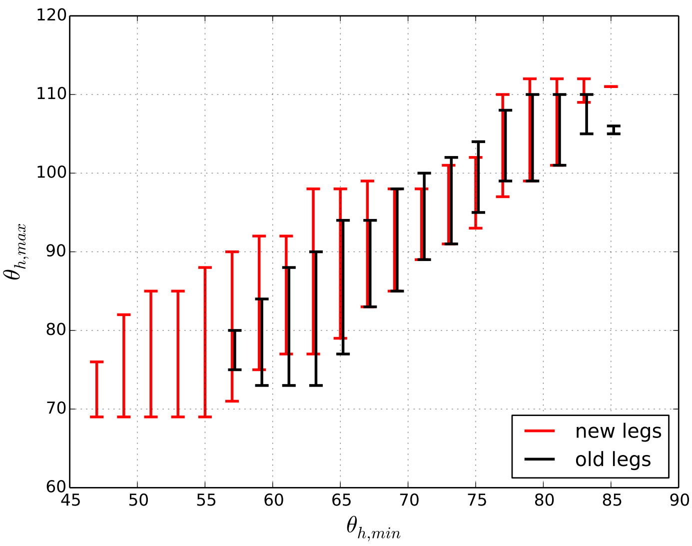


Figure 5. Parameter range for walking on flat ground. Increased $\theta_{h,min}$ in 2 degree steps and explored range of possible $\theta_{h,max}$ for each step.The other gait parameters remained unchanged.

The plot shows that flat feet and compliant ankles result in a much bigger parameter range for stable gaits. It can cope far better with smaller $\theta_{h,min}, \theta_{h,max}$ parameter pairs, that is, with more leaned back posture. The smallest possible value of $\theta_{h,min}$ found is 47 for the new legs, while it is only 59 for the old legs. Moreover, for those values of $\theta_{h,min}$ where both set-ups have stable parameters, $\theta_{h,min} \in [59, 85]$, the new legs lead to more stable values of $\theta_{h,max}$ for the more leaned back positions.
Going from the leaned back positions (small $\theta_{h,min}$) to the leaned forward positions (big $\theta_{h,min}$), the difference between both set-ups' range of stable parameters decreases. At the extreme end of high $\theta_{h,min}$-values, the old legs

allow for smaller step sizes (difference between $\theta_{h,min}$ and $\theta_{h,max}$) than the new legs.

To further compare both set-ups' gait stabilities, we investigated their success in overcoming obstacles. From the measured parameter ranges in fig.5, we picked several parameter pairs $(\theta_{h,min}, \theta_{h,max})$. We picked 6 parameter pairs for the old legs and 9 for the new set-up, trying to cover its bigger range better. Four square-shaped obstacles were used, differing in height but with equal sidelengths of 5 cm. For each pair of parameters 10 trials per obstacle were conducted. This results in 60 trials per obstacle for the old legs and 90 trials per obstacle for the new legs. The resulting success rates are shown in fig.6. The new legs outperformed the old ones for the

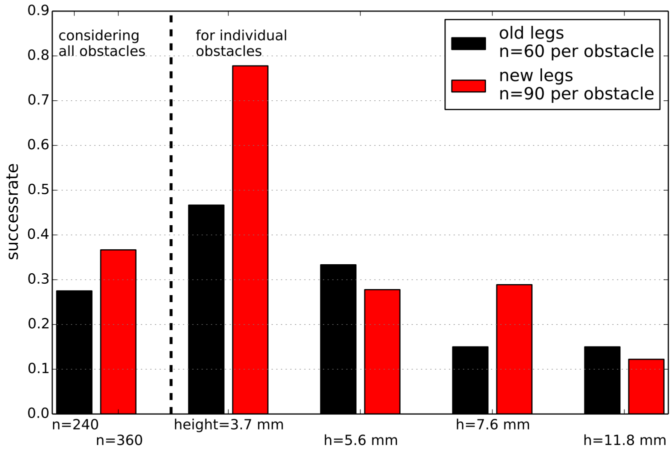


Figure 6. Success rates for dealing with obstacles with different heights.

lowest and the second heighest obstacle. For the other two obstacles their successrates are quite similar, the old legs' rate being only slightly higher in both cases.

4. Discussion and Outlook

The old legs' range is mostly lying inside the new ones', but exceeds it at some points, allowing for smaller step sizes (smaller difference between

$\theta_{h,max}$ and $\theta_{h,min}$). This indicates that leaning forward postures may be necessary for the old set-up in contrast to the new set-up. RunBot can handle leaning back postures (which should result in slower walking speed) better using flat feet and compliant ankles, since the ankle springs help conserving more energy for the forward movement.

In overcoming obstacles the new legs exceeded the old legs' performance slightly. Overall this experiments were very challenging, since the existing proprioceptive sensors cannot detect obstacles. Therefore it needs to rely only on its mechanical legs to deal with obstacles.
Although the new lower legs and the new ground contact switches set up a stronger basis, to tackle obstacle overcoming in future experiments, new sensors need to be added, to either remotely detect obstacles beforehand or increase the chance of detecting obstacles instantly after hitting them.

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