Proceedings of the 2nd International Symposium
on Adaptive Motion of Animals and Machines,
Kyoto, March.4-8, 2003

Design and Construction of MIKE; a 2D autonomous biped based on passive dynamic walking

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Abstract

For research into bipedal walking machines, autonomous operation is an important issue. The key engineering problem is to keep the weight of the actuation system small enough. For our 2D prototype MIKE, we solve this problem by applying pneumatic McKibben actuators on a passive dynamic biped design. In this paper we present the design and construction of MIKE and elaborate on the most crucial subsystem, the pneumatic system. The result is a fully autonomous biped that can walk on a level floor with the same energy efficiency as a human being. We encourage the reader to view the movies of the walking results at http://mms.tudelft.nl/dbl.

Keywords: Passive Dynamic Walking, Biped, Autonomous, Pneumatics, McKibben muscle, pressure regulator.

1. Introduction

We are performing research into bipedal walking robots with two long-term goals in mind. First, we expect that it increases our understanding of human walking, which in turn can lead to better rehabilitation of the impaired. Second, autonomous walking robots could greatly enhance the entertainment experience for visitors of theme parks and the like. Both long-term goals impose identical requirements on bipedal robots. They should be anthropomorphic in function and appearance, their locomotion should be robust, natural and energy efficient, and they should be easy to construct and control.

A solution for energetic efficiency is the exploitation of the 'natural dynamics' of the locomotion system. In 1989 McGeer [6] introduced the idea of 'passive dynamic walking'. He showed that a completely unactuated and therefore *uncontrolled* robot can perform a stable walk when walking down a shallow slope. His most advanced prototype (Figure 2) has knees and a hip joint, which connect in total four thighs and shanks (with

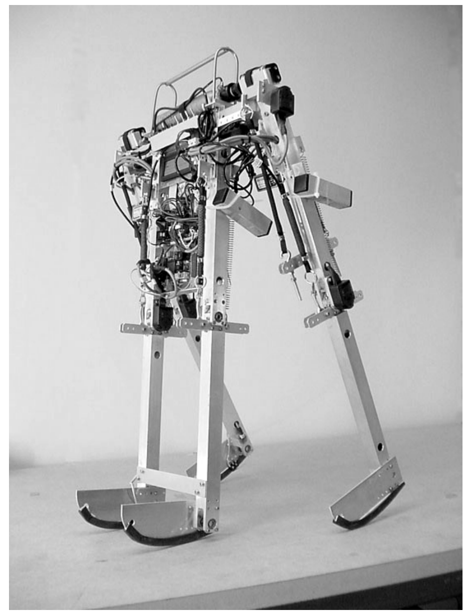

Figure 1: 2D biped prototype MIKE.

Figure 2: Close copy of McGeer's walker by Garcia et al.

rigidly attached circular feet). The inner two legs form a pair and so do the outer legs, so that the machine essentially has 2D behavior.

We believe that passive dynamic walking should be the starting point for successful biped design. For a human-like robot walking on level ground, a necessity of actuation arises for energy input (instead of walking down a slope), and for stabilization against large disturbances. We propose a robot design that can perform a robust motion as a result of the passive dynamics, while the actuators only compensate for friction and impact energy losses.

We are materializing this combination of passive dynamic walking and actuation in the form of our new prototype MIKE (see Figure 1). On top of the specifications of McGeer's machine, MIKE is provided with McKibben muscles (pneumatic actuators) in the hip and knee joints that can provide energy for propulsion and control, thus eliminating the need for a slope and providing an enhanced stability. In this paper we will describe the design and construction of MIKE, focusing in sections II - V on the key construction elements; foot shape, McKibben muscles, pneumatic system, pressure control unit. Section VI presents walking experiments of MIKE walking downhill and on a level floor.

2. Foot Shape

2.1. Foot shape in literature

The human foot is shaped so that the center of pressure (the average contact point) travels forward during the progression of a walking step. This effect is known as 'foot roll-over'. When replicating the human foot for prostheses or for walking robots, many designers apply a curved foot sole with an approximately circular foot roll-over shape. For contemporary foot prostheses, Hansen *et al.* [4] shows the effective foot roll-over shapes of different makes. From his graphs we conclude that they all have a foot radius of 30-35 [cm]. Apparently that was empirically determined to be the best foot shape.

In passive dynamic walking robot research, many computer models and prototypes are equipped with circular feet, following McGeer's example. McGeer [6] determined the effect of the foot radius on the local stability (i.e. small disturbances) of his walkers and so concluded that a foot radius of about 1/3 of the leg length would be a good choice. However, we argue that a good local stability does not imply a good disturbance rejection for larger disturbances. As an example, we compare the findings of Garcia *et al.* [2] on the simplest walking model with our own. Their simplest walking model was equipped with point feet (foot radius equal to zero), and showed stable downhill walking for slopes up to 0.015 [rad]. However, when studying the allowable size of the disturbances for that model [10], we found that even a 2% change of the initial stance leg velocity could make the model fall over. In conclusion, more information is needed about the effect of the foot roll-over shape on the allowable size of the disturbances.

2.2. Test machine for foot roll-over shape

We built a test machine (Figure 3) to answer the question: 'with what foot radius can the largest disturbance be handled?' The test machine weighs 3 [kg] and is, with a leg length of 38 [cm], approximately half the size of MIKE. It has no knees, the only joint is at the hip. The test machine was placed on a shallow slope with a disturbance half-way. The disturbance was realized by lowering the second half of the walkway. The stability was quantified as the largest amount of lowering that the test machine could still recover from and continue walking to the end of the slope.

Figure 3: Test machine to determine the effect of the foot radius on the stability.

We built four different sets of feet with radii from 50 [mm] to 380 [mm], but limited the foot length to about 8 [cm]. The results are plotted in Figure 4. Apparently, the larger the foot radius the better, as coincides with intuition. Of course, when the foot length is limited, there is no gain in increasing the foot radius above a certain value;

the walker would just spend more time on the heel and toe.

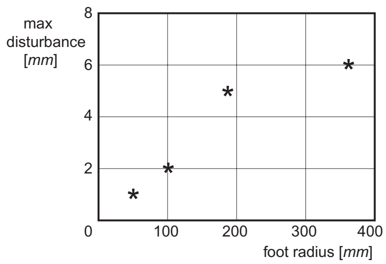

Figure 4: Stability results of the test machine tested with four different foot radii: 50, 100, 190 and 380 [mm] with a foot length limited to approx. 8 [cm]. Apparently a larger foot radius is always better.

Figure 5: In practice, we obtained the best results with a foot radius of 25 [cm], a foot length of 13 [cm], and a forward displacement of 6 [cm]. The foot switch allows the controller to adapt to the actual step time by registering the exact instant of heel strike.

2.3. Construction

Theoretically, MIKE needs feet with a radius as large as possible. In practice however, there is a limitation to the length of the foot due to the required foot clearance. If the foot is long, bending the knee will not result in enough clearance for the swing leg, but rather in the opposite. Based on the empirically determined prosthetic foot shape and some experimenting with MIKE, eventually we decided on a foot radius of 25 [cm] and a length of 13 [cm]. This is pretty close to McGeer's recommended 1/3 of the leg length.

Another practical consideration is the place of attachment of the foot to the shank. McGeer shifted the feet somewhat forward from the center, so that the passive reaction torques would keep the knees locked during the stance phase. We don't need this, for we have muscles to actively extend the knees. However, empirical study showed that the best stability results were obtained indeed with the feet shifted forward about 6 [cm], see Figure 5.

3. McKibben Muscles as Adjustable Springs

3.1. Background and requirements

For autonomous systems, it is crucial to apply lightweight actuators. For a passive dynamic walker, another requirement is that the actuators should not interfere with the passive swinging motions of the legs. McGeer says the following about this matter: "The geared motors or fluidic actuators used on most mechanical bipeds do not satisfy this requirement; lift one of their legs, and it will hang catatonically or, at best, grind slowly to a halt at the bottom of its swing." We chose to use pneumatic McKibben muscles as actuators that fulfill these requirements. In comparison to other alternatives, such as commercially available pneumatic cylinders, McGeer's LITHE [7], Direct Drive torque motors, or MIT Leglab's Series Elastic Actuators [9], the McKibben muscles are very lightweight and simple in construction and application.

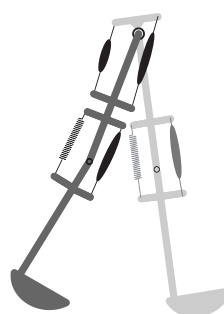

Figure 6: Overview of the McKibben muscles on MIKE. Each muscle drawn represents two muscles performing the same function in the machine.

Under constant pressure the McKibben muscles behave like a spring with low hysteresis. Because the muscles can only provide tension force, we use them in a pair of antagonists, counteracting on the same passive joint (see Figure 6). Increasing the internal pressure results in a higher spring stiffness, which in turn increases the natural frequency of the limb.

3.2. Operating principle

A McKibben muscle consists of flexible rubber tube, covered by a weave of flexible yet non-extensible threads, see Figure 7. The operating principle is best explained when starting with a non-attached, pressurized muscle. If from that state the muscle is extended, the non-extensible threads are forced into an orientation with a smaller inter-thread angle, thus decreasing the diameter of the muscle. The cumulative effect of

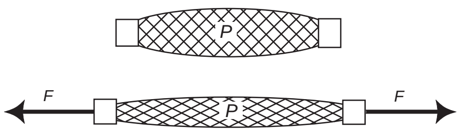

Figure 7: Operating principle of McKibben muscles.

muscle extension and diameter reduction is a decrease of muscle volume. Against an assumed constant muscle pressure, reducing the muscle volume costs work. This work can only be supplied by a tension force in the muscle attachments. In other words; muscle extension causes a counteracting force, which makes the muscles act like tension springs. A more detailed study of the McKibben muscle used as an adjustable spring can be found in [11], where the relation between muscle extension and tension force is presented as:

$$F = \frac{b^2 P'}{2\pi n^2 L_0} \Delta L \tag{1}$$

with F = muscle force, b = length of weave threads, P' = relative muscle pressure, n = number of turns of a thread, L_0 = muscle rest length, and ΔL = relative muscle extension. This relation reveals the most important characteristics of a McKibben muscle:

- The muscles behave like linear springs,
- The spring constant is proportional to the muscle pressure.

3.3. Technical realization

McKibben muscles are based on a simple concept and are generally easy to construct. However, it is our experience that the choice of materials and connectors is important for the muscle lifetime. Therefore, we use commercially available muscles (Figure 8) made by the Shadow Group [3], which they sell at £6 each. The muscles weigh less than 10 grams and can produce a force of 40 [N] at 0.40 [MPa].

Figure 8: Photograph of the actual Shadow group McKibben muscle.

3.4. Results

Figure 9 shows the mechanical behavior of one type of Shadow muscle (6 mm diameter, 150 mm length) at different pressure levels. Note that indeed the muscles behave like linear springs (in this range). Also, note that there is a small but noticeable hysteresis-loop, representing losses mainly due to friction between the scissoring threads and the rubber tube.

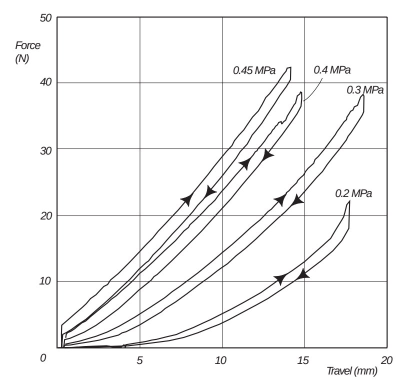

Figure 9: Measurements on Shadow muscles.

4. Pneumatic System

4.1. Background and presumptions

Because a McKibben muscle needs pressurized gas for functioning, our autonomous biped MIKE needs to be provided with an efficient, lightweight and properly working pneumatic system. First of all, we have to carry along our own reservoir of pressurized gas. The gas should be stored at saturation pressure in order to keep the necessary container volume as small as possible. Secondly, the high pressure from this container has to be reduced to various operation pressure levels between 0.1 [MPa] and 0.4 [MPa].

Minimizing gas consumption helps to increase the autonomous operation time. Van der Linde [11] developed the so called 'Actively Variable Passive Stiffness'-system. This system includes a solenoid 3/2 valve that switches the internal muscle pressure between two preset pressure levels. In this way, only a small volume of gas is needed every time the muscle is activated, because the muscle pressure is never completely vented to ambient pressure.

4.2. Requirements

To have time for proper experiments, we need a few minutes of autonomous operation time on one gas container. Measurements on the amount of exhaust gas, during a pressure decrease from 0.35 to 0.15 [MPa] in one muscle, tell us that we need 44 milligrams CO_2 per actuation. During each step 4 muscle activations take place, so that we need 176 milligrams of gas each step. The step time is 0.6 seconds. By choosing an ISI CO_2-bulb [5] with 86 grams of gas, we have an acceptable 5 minutes of continuous experimental time.

Because our goal is to build a transportable and easy to handle biped, we (intuitively) put the maximum total weight on 7 kg. Regarding the amount (and weight) of the electrical and mechanical subsystems, a total weight of the pneumatic system of 1 kg seems to be acceptable.

Since the muscle pressure is directly related to the stiffness, it is important to be able to control the pressure levels with high accuracy. A relatively short response time is needed to make it possible to execute control actions during a step time of 0.6 seconds.

4.3. System overview

The pneumatic system provides the actuation for our prototype MIKE. The pneumatic system receives input from the on-board controller in the form of valve control signals. The controller determines when each muscle is activated or deactivated. The two respective muscle pressures are to be preset manually when tuning the prototype. The output of the pneumatic system obviously has the form of joint torques that influence the passive dynamic leg motions.

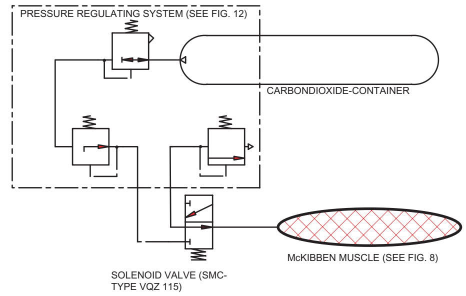

Figure 10: Overview of the pneumatic system on MIKE.

To provide for this desired input-output behavior, the pneumatic system consists of four components (see Figure 10): 1) gas container, 2) manually adjustable pressure reduction valves, 3) electronically controlled 3/2-way switching valves, and 4) McKibben muscles. The pressure reduction system is the most crucial part of the pneumatic system. We developed this system and will present it in the next section. For the valves we use the pilot pressure operated VQZ 115 valves from SMC [8]. Although these are about the most efficient commercially available valves, they still consume 0.5 Watts each. We are encouraging suppliers to develop more efficient valves. The McKibben muscles have been discussed in the previous section.

5. Pressure Control Unit

5.1. Background and requirements

The pressure control unit must be able to regulate the desired muscle pressures accurately and fast (well within the step time of 0.6 seconds). Secondly, application in an autonomous biped requires a compact, lightweight and gas efficient solution.

There are two commercially available regulator principles, each of which can only fulfill part of the above requirements. The indirectly controlled pressure regulators (flapper-nozzle type) provide fast and accurate pressure control at the cost of a high internal gas consumption and relatively large physical dimensions. Directly controlled pressure regulators (piston type) are generally small and lightweight and need no extra gas supply for internal consumption, but are not sensitive and accurate enough for our application. We used the directly controlled principle, as small size and gas efficiency are the most important requirements, and minimized the disadvantages.

5.2. Operating principle

The piston type pressure regulator is drawn in Figure 11. A valve separates the input pressure from the output pressure. The output pressure acts on a spring loaded piston, where the manually adjustable spring load represents the output pressure level. If the output pressure falls below this preset value, the spring loaded piston opens the valve and the output pressure level is restored. To ascertain that the pressure regulator is sensitive, it needs to be constructed with a high ratio of A:C (see Figure 11) and with low internal friction.

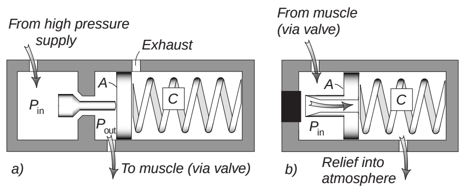

Figure 11: Working principle of pressure regulator (a) and pressure relief valve (b).

The low preset pressure level is realized by integrating a separate pressure relief valve (see Figure 11) in the muscle outlet. The spring loaded piston in the pressure relief valve is open as long as the muscle pressure is higher than the preset level (drawn situation).

5.3. Technical realization

The principles discussed above are translated into functioning prototypes. Experiments have convinced us that the required relatively high accuracy cannot be met by a single-stage pressure regulator, due to pressure overshoot and steady state offset. Therefore we have divided the pressure reduction in two stages, see Figure 12.

First, one main pressure regulator directly on the gas bulb brings the pressure from 5.8 [MPa] to about 1.0 [MPa]. Second, a second-stage reduction from 1.0 [MPa] to 0.2 – 0.4 [MPa], with 4 different preset manually adjustable pressure levels, is realized in the input pressure control block ('IN', Figure 12). In these valves, the pistons are equipped with diaphragms to minimize friction effects and to provide the required sensitivity and accuracy. The output pressure control block ('OUT') includes four adjustable pressure relief valves. Basically the same piston construction as in the input pressure reduction valves has been used. The two pressure-control blocks together weigh about 180 gram and have a volume of less than 8 x 5.5 x 1.5 cubic centimeter.

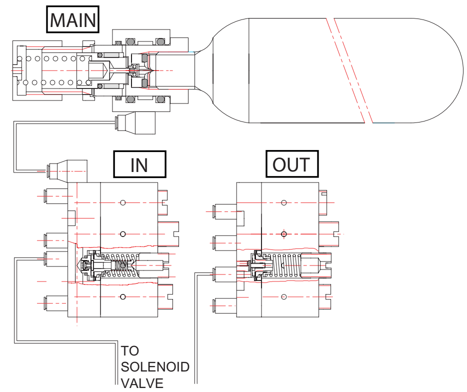

Figure 12: Technical drawings of pressure reduction system.

5.4. Results

After assembling the complete pneumatic system, it is possible to evaluate the behaviour by measuring the muscle pressure in time, during a switching-action of the described solenoid valve. Figure 13 shows the dynamic response of the complete system (see Figure 10) when pressurized from 0.15 [MPa] to 0.35 [MPa] and back. We obtain an accuracy/repeatability of about 10 [kPa], and a relatively slow response as was to be expected with the choice of pressure regulator type. However, the system is fast enough according to the successful walking results.

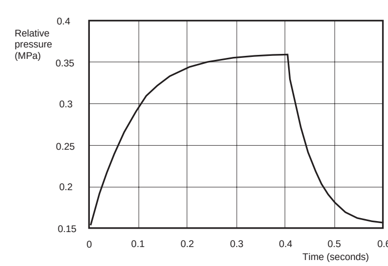

Figure 13: Dynamic response of the complete pneumatic system.

6. Walking Experiments

6.1. Downhill walking with rigid knees

We performed walking experiments with an increasing number of active degrees of freedom, starting with walking down a slope with rigid knees. With rigid knees, foot scuffing is inevitable. To eliminate this problem for our initial experiments, we constructed 'stepping stones' at the expected footfall locations. Together with the slope angle this required some tuning, eventually resulting in stable walking with steps of 0.24 [m] at a slope angle of 0.06 [rad].

In this setting, we could start with experiments with rigid knees, similar to the testing machine in Figure 3. With the Agilent HEDS-5540 incremental optical encoder on the hip joint, the hip angle was recorded during a successful run as shown in Figure 14. As is apparent from the figure, the gait was not symmetrical. When the middle legs were swinging (positive hip angle), the step was much longer in duration. Heel strike only occurred when they were already far on their way back, noticeable by the small bump (impact shock) in the graph. It is not clear whether this asymmetry resulted from a non-perfect launch or from the machine's natural dynamics. A simulation study in the near future should reveal this. Although not symmetrical, the emergent gait was encouraging enough to continue with experiments with bending knees.

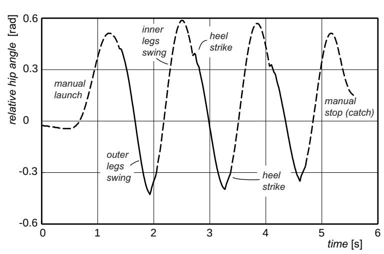

Figure 14: Walking results with stiff knees on a floor with stepping stones on a 0.06 [rad] slope .

6.2. Downhill walking with bending knees

By bending the knee for the appropriate time interval during the swing phase of a leg, the prototype can gain just enough foot clearance for continuous walking without stepping stones. As McGeer has shown, it is possible to obtain the appropriate timing with pure passive dynamics by tuning the mechanical properties. In our experience, it is then essential to keep the center of mass of the shank very close below the knee joint. However, we want the ability to actively interfere with the knee motion for future rough terrain walking experiments, so MIKE was provided with knee-stretching muscles. Having these muscles there anyway, we decided to actively control the knee motion rather than completely rely on the passive dynamic motion.

The knee is stretched actively with a McKibben muscle counteracted by a passive spring, see Figure 6. The default knee muscle pressure is 'high' (0.35 [MPa]), which is switched to 'low' (0.08 [MPa]) at the other leg's heel strike, and switched back to 'high' after an empirically determined 400 [ms]. With this activation pattern we obtained steady walking for the entire length of the slope (5 [m]) with the appearance to be able to continue to walk indefinitely, see Figure 15. It is easy to launch the prototype by hand, so we would call it 'pretty stable'. We have not yet performed experiments to determine the exact stability of the gait.

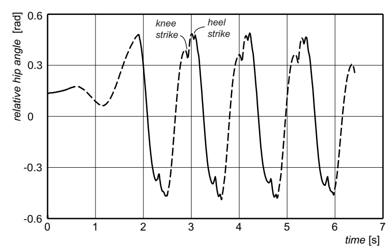

Figure 15: Walking results with active knees on a 0.06 [rad] slope. The prototype completes 7 symmetrical steps until the end of the walking surface.

In these walking experiments MIKE has about the same specific resistance as a walking human being, using about 10 [W] to pull its 7 [kg] along at a speed of 0.4 [m/s]. The energy consumption consists of three components. First, the propulsion is obtained from gravity by walking down a 0.06 [rad] slope, which counts for 1.6 [W]. Second, the knee muscles use approximately 0.4 [MPa] CO_2 which accounts for 5.3 [W]. Actually, to keep the storage volume small, the CO_2 is stored and supplied at the saturation pressure, 5.8 [MPa]. The inevitable loss of energy in the process of pressure reduction from 5.8 to 0.4 [MPa] is not taken into account. Third, the prototype is equipped with a number of sensors and a a low power (less then 1 [W]) Strong-Arm based Linux machine (the LART [1]), which use together about 3 [W]. Obviously, the bulk of the energy consumption goes to the architecture for improving the stability even when using low-power components. We hope to increase the walking stability without increasing the energy consumption even more by using the timing of the muscle activations as a control parameter [11].

6.3. Walking on level floor

Finally, we activated the hip muscles and leveled out the walking surface. That made the robot lose its natural tendency to tilt and walk forward, so we had to shift the center of mass forward with a few centimeters. The hip muscles are the same as the knee muscles, but operate as antagonistic pairs. When heel strike is detected one muscle is set to high, its antagonist to low, so that the swing leg is pulled forward. We have not yet performed accurate measurements on the torque that the muscles exert on the hip, but it is estimated to be below 2.5 [Nm], approximately the same as the maximal torque from gravity. This simple form of hip control is sufficient to obtain a robust gait, see [12].

Mike performs a steady walk on a level floor, as demonstrated with video's at http://mms.tudelft.nl/dbl. It can handle irregularities in the terrain, such as the sidewalk in front of our building.

With the ability to walk on level ground, we finally had the opportunity to perform an endurance test. On the 86 grams of CO_2, MIKE can walk 3.5 minutes. After a continuous walk that long, the main pressure regulator is deeply frozen due to gas expansion; apparently it is a little undersized for the actual gas flow.

7. Conclusion

We started this research with the question: “How to keep the actuators and energy storage device lightweight enough to enable autonomous operation for a walking biped?” Our solution is provide the biped with a pneumatic actuation system. This form of actuation is successful when applying the following two ideas: 1) use McKibben muscles as adjustable springs and 2) develop a compact and well performing pneumatic system. With these developments we were able to construct a fully autonomous biped. We have succeeded in making it walk in a stable manner on a level floor, see http://mms.tudelft.nl/dbl.

Now that we have concluded the first phase of this project, we are aiming at the following goals: first to add an upper body while maintaining passive dynamic properties, and finally to extend to three dimensions.

Acknowledgements

This research is funded by the Dutch national technology foundation STW. Thanks to Richard van der Linde, Arend Schwab, Dick Plettenburg, Frans van der Helm, Erik Mouw and Jan-Derk Bakker.

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