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Active Knee-release Mechanism for Passive-dynamic Walking Machines and Walking Cycle Research

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***Abstract*— Passive–dynamic walkers are mechanical devices that walk down a slope without motors or controllers. In this paper we present our research in two distinctive parts. First, a design improvement on the classical four-legged passive-dynamic walking machine and second, an investigation on the timing of different stages in the human walking cycle and comparison of the results with the results obtained from our walker. We built a four-legged passive-dynamic walking machine with its inner and outer legs connected rigidly two by two, making it equivalent to a biped machine from a dynamics point of view. It features a new mechanism for an active release of the locked extended knee instead of using the more common knee-locking via suction cups mechanism. We conducted a series of experiments with this modified walker in which we counted the steps it made while walking down an incline. We compared the results with a previous design of the knee-locking mechanism that used permanent magnets. The improved model made an increased number of successful walks down the slope from which we concluded that the new active release mechanism is more reliable and easy to use and set up. For the walking cycle investigation, we put visual markers on a person walking casually down the same slope that we used for the walker experiments. We took a video of that person and measured the times between different events in one walking cycle. We calculated the average time intervals and made a comparison between the test subject and our walker within one cycle. We feel the timings derived from this investigation can be used to make the gait of our walker more human-like.**

I. Introduction

ONE of the big and still, unsolved problems of robotics is achieving efficient and stable bipedal walking. There are two main strategies used to control walking. First, the traditional approach is to control the joint-angle of every joint at all times. Crucial disadvantages of this type of strategy are that it results in a non-efficient gait in terms of energy consumption [1], it requires complex controllers and programming, and this strategy often results in gaits that are unnatural compared to the human gait. Second is a somewhat new strategy called passive-dynamic walking, introduced by Tad McGeer [2] in the late 80's, early 90's. His main inspiration came from walking toys created earlier, which use the same principle. One such walking toy schematic reprinted by McMahon [3] is shown in Fig. 1. A walker based on passive-dynamic walking principle uses its own mechanical dynamics properties to determine its movement. Such walkers can walk down slight inclines without any actuators, sensors or controllers. The energy that is necessary in order to sustain the walking motion is provided by gravity. The force of gravity is also enough to offset the losses due to impact of the feet to the ground and friction. The advantages of passive-dynamic walking are high-energy efficiency, simple or no control, and a very human-like gait. The main disadvantage is that because they are not actively powered, they can only walk on downhill slopes. This disadvantage can be eliminated by modifying the original design of the walkers to include actuators to supply the necessary power instead of gravity [4, 5]. This enables them to walk not only on downhill, but on level and uphill surfaces as well. This possibility greatly increases the prospects of practical application. These types of walkers have been investigated by people such as Andy Ruina of Cornell University [6], Steven Collins of University of Michigan [7] and the Bio-robotics Lab at the Technical University of Delft [8].

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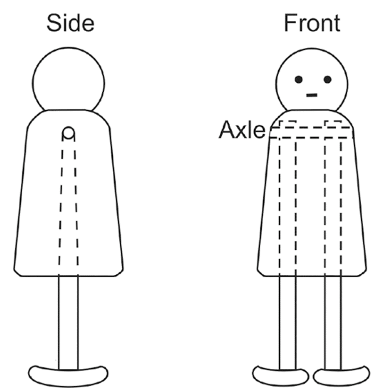

Fig. 1. Walking Toy Schematic by McMahon [3].

We built a four-legged passive-dynamic walking machine, shown in Fig. 2, with its inner and outer legs connected rigidly two by two, making it equivalent to a biped machine in terms of dynamics. We used it to test our design concepts for two different knee-locking mechanisms: one with a magnetic lock and the other featuring an active release system. Our goal was, using the walker as a testing platform, to develop a knee, which is simpler, more reliable, and more robust than existing designs used in other passive-dynamic walkers. We believe that our active release knee design is in fact much better than the more commonly used suction cups approach.

Fig. 2. Our Four-legged Walker.

The three purposes of this paper are to; 1) present our design of a knee-locking mechanism with an active release for passive-dynamic walking machines, 2) compare it with an older design that uses permanent magnets, 3) to introduce and compare experimental results from research on the timing of the human walking cycle and the walking cycle of our walker. To compare the new and old knee designs, we performed a series of experiments where the walker's steps were counted as it walked down an incline. The experiments were run using both mechanisms on the same four-legged passive-dynamic walker. According to our results, the new knee design proved to be more reliable. The walker made more successful walks and was easier to set up. We also present the results from our research on the timing of the human walking cycle and the walking cycle of our walker with hopes of using the experimental data collected to adjust the timing of the walker in order to make its gait as human-like as possible.

II. Knee-locking Mechanism Design

A. Magnetic Knee-locking Mechanism

In our first attempt to improve the knee-locking mechanism of a passive-dynamic walker we developed a knee using permanent magnets, postulating that the magnetic force would be strong enough to lock the knee and keep the leg extended. The design, a simplified representation of which is shown in Fig. 3, is presented in detail in [9]. We speculated that by changing the distance between the magnets and the steel plate we could control the strength of the magnetic force and thereby control the strength of the locking and the release time. Our experiments, however, showed that it was very difficult to precisely adjust this setting, which resulted in unreliable performance of the machine in this configuration. In the end, we were forced to make radical changes to this design, which led to the design of a non-magnetic, active release mechanism, which is much more robust and reliable.

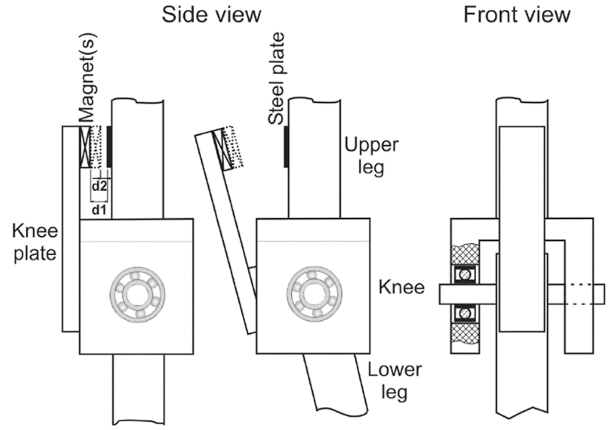

Fig. 3. Magnetic Knee-locking Mechanism.

B. Active Knee-locking Mechanism

We designed a simple and low weight knee-locking mechanism [10]. The locking mechanism is constructed of acrylic, ABS, steel, and aluminum. The knee-locking mechanism consists of a knee (A), knee plate (B), locking axle (C), locking hook (D), base plate (E), and a DC motor (F) as shown in Fig. 4. The entire knee-locking and release mechanism was designed in 3D in SolidWorks 2007 and cut on a CAM machine equipped with a computer running VectorWorks 12 software. The knee is cut from aluminum, the knee plate from acrylic, the locking axle from steel, and the locking hook and the base plate are cut from ABS.

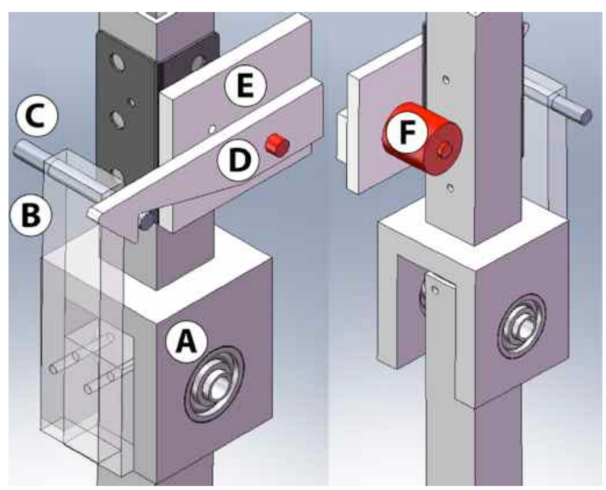

Fig. 4. 3D Schematics of the Knee-locking Mechanism.
A-knee, B-knee plate, C-locking axle, D-locking hook, E-base plate, F-DC motor.

The locking action is done passively. As the swing leg extends before hitting the ground, the locking axle hits the front edge of the locking hook, lifts it, and then the latter comes back down to lock the axle, effectively locking the knee itself. The locking hook is balanced by a counter weight (not shown on the figure) in such a way that it returns to its initial position after the locking axle has lifted it. Just before the stance leg lifts from the ground and starts to swing, the foot switch comes into contact with the ground and switches to ON position, thus turning on the power for the DC motor which lifts the locking hook and releases the knee. Immediately after the leg lifts off the ground and starts swinging, the foot switch returns to OFF position, the power is cut and the locking hook returns to its initial position.

The electrical circuitry is shown in Fig. 5. We use four Tamiya RC260 type DC motors (M), which have low energy consumption, being powered by two standard AA 1.5V batteries each. They have no gearbox, which results in a very low torque. This, and the necessity for low energy consumption, forms the reasons behind our decision to create such a low-weight mechanism. High energy consumption is one of the main problems when designing humanoid robots. This approach allows us to reduce weight, and thereby energy consumption, without losing the ability to walk. The foot switch is mounted on the front part (the toe) of the foot by means of an adjustable plate that allows for changes in the position of the switch and ultimately the activation moment. When the stance leg passes behind the swing leg, the switch makes contact with the ground and switches from OFF to ON, thus activating the DC motor which lifts the locking hook and initiates the knee-release procedure. The on / off switch is used for turning on and off the entire system.

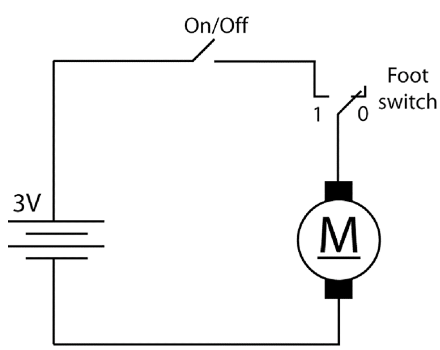

Fig. 5. Electrical Circuit for the Knee-release Mechanism.

One walking cycle of the machine is illustrated in Fig. 6, where “O” and “I” mean outer and inner leg respectively. At moment (1) after the stance leg is passed by the swinging leg and becomes the back leg, the foot switch mounted on its toe activates and turns on the DC motor, which lifts the locking hook, and releases the knee. At moment (2), as soon as the stance leg becomes the swing leg and starts to swing forward, the foot is no longer in contact with the ground. The foot switch turns off the power to the DC motor and the locking hook returns to its starting position, waiting for the next cycle. At moment (3), the knee of the swing leg reaches its full extension and the knee hook locks the knee just before it hits the ground, keeping the leg in its extended position as it becomes the stance leg. Ideally, the knee release should be done just after the swing leg touches the ground, but in practice this is difficult to achieve and coordinate precisely, which is why the release occurs just before that moment.

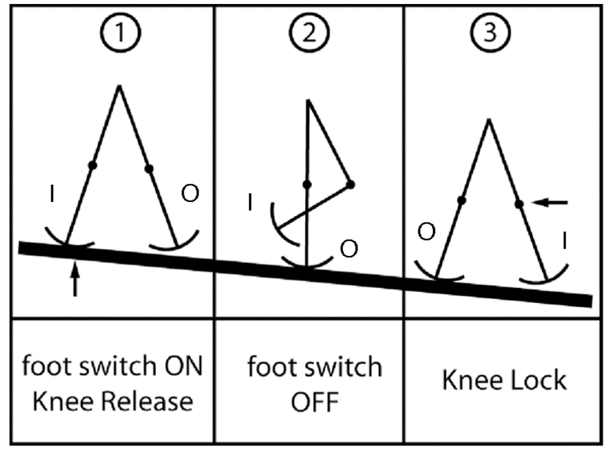

Fig. 6. Simplified Walking Cycle of Our Passive-dynamic Walker.

Even with this design, which is quite effective in locking the knee, problematic bouncing of the knee can occasionally be observed. When the leg extends too fast and the knee plate and locking axle hit the locking hook with high velocity, the locking hook does not have enough time to close and lock the knee. A failure to lock the knee means premature ending of the walking cycle and a failed trial. In order to keep this effect to a minimum, we have added a 1mm thick rubber pad between the knee plate and the top part of the knee to cushion the hit and decrease the speed.

III. Experimental Results

A. Comparison of the Two Knee-locking Mechanisms

To compare the magnetic and active-release knee-locking mechanisms experiments were conducted with the same walker, built from square aluminum tubes for the legs, and 2 millimeters thick steel plate for the feet [9]. For the thighs and lower legs we used 2.5 by 2.5 centimeters square aluminum tubes with lengths of 34 and 43.5 centimeters respectively. The total height of the walker is 89 centimeters and the radius of the feet is 12.3 centimeters. The knees were outfitted first with magnetic locks and then with the newly developed active mechanism. The walker was set on a ramp, which measures 3 meters in length, 90 centimeters in width, and has a 3° angle grade relative to the ground. The ramp is covered with a rubber mat to reduce the chance of foot slippage. Other reasons for failure during experiments include incorrect start of the walker, as it is started manually; and failure of the knee-locking mechanism to lock or unlock.

We performed several sets of 100 trials (walks) down the ramp for both knee-locking mechanisms and counted the steps that the walker completed each time. We denote a trial as successful if the walker manages to make five to seven steps before it exits the ramp. While five to seven steps may seem short, we postulate that after five steps, the walker has achieved a steady gait, and would ideally continue assuming a longer ramp existed. However, the impracticality of a longer ramp led us to set this number of steps as the criteria for deciding walk success.

Fig. 7 shows a comparison between the two knee-locking mechanism designs in terms of number of steps made in each of the hundred trials.

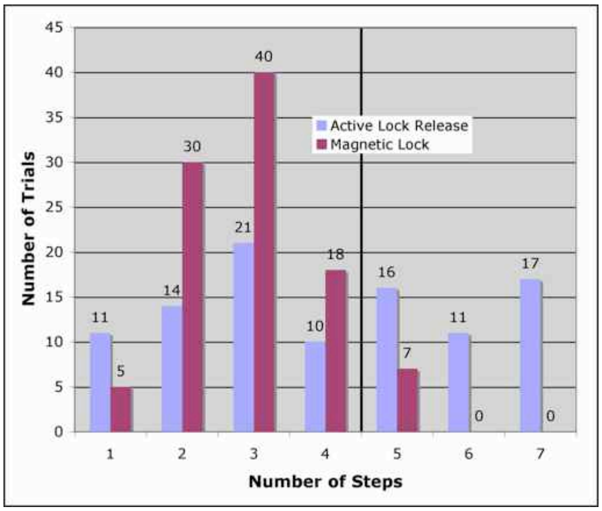

Fig. 7. Comparison Between the Experimental Results of the Two Designs of Knee-locking Mechanisms.

As the results show, using the new knee-locking mechanism with active release, we can achieve a reasonable amount of successful trials. Out of a hundred trials, the walker achieved an average of forty-four successful walks with the active release system, while the magnetic approach resulted in only seven. In addition to the higher number of successful trials, using the new mechanism produces fewer unsuccessful trials than the magnetic knee-lock mechanism. The only exception is in the case where the walker fails on the first step. In reality, it is very difficult to judge whether the higher number of failures with the new mechanism are due to some design problems or an effect of the subjective start, performed by the operator. We assume that failure on the first step is a result of a bad start performed by the operator and exclude these failures from our design analysis.

B. Measurements of the Human Walking Cycle Times

There are two main theories that are widely accepted in the study of walking: the six determinants of gait and the inverted pendulum theory (Fig. 8a & b)[11].

According to the six determinants of gait theory, displacement of the center of mass (COM) of the body in vertical and horizontal (side to side) position is costly in terms of energy use. It states that a set of kinematic features in the body work in coordination to reduce the side and vertical movement of the COM to a minimum. On the other hand, the inverted pendulum theory states that it would be more economical if the stance leg moved like an inverted pendulum. In this way the COM would move on an arc trajectory. It is obvious, that the two theories contradict each other, and it is necessary to find a single theory that either unifies the two existing ones or proves one of them to be correct and disproves the other. The six determinants of gait have been accepted as a fact for 50 years without being subjected to experimental testing [11]. A simple approach, which also provides easy prediction of the results, should be used to find out which theory is more sensible.

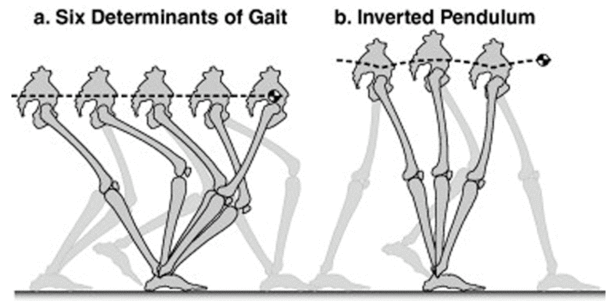

Fig. 8. Walking Theories [11].
(a) – Six determinants of gait; (b) – Inverted pendulum.

Dynamic walking is one such approach. Dynamic walkers in the sense of our research are based on passive dynamics with minor actuation added in order to compensate for the energy loss in the step transition phase. The six determinants of gait features a relatively flat trajectory of the COM, but requires substantial work by the legs and high knee torque. The inverted pendulum-like gait requires very little work and torque, but requires a transition between the two steps. The dynamic walking approach helps resolve the conflict between the two major theories of human gait. As shown in experimental results [11], the inverted pendulum approach, extended using the principles of dynamic walking, models the human gait in a manner that corresponds more closely to observations and measurements. We have decided to base our research on that extended version of inverted-pendulum walking theory and assume that the gait of a person is similar to, and its characteristics can be directly compared to, those of a walking machine built by the same principles, such as our walker.

When we designed our passive-dynamic walker, we wanted to model the human gait as closely as possible. That, of course, means that the human walking cycle must be researched and some observable data collected. How long it takes? What are the time intervals between different moments like heel strike and knee unlock? How does the gait look in general? When we have sufficient data on the walking cycle, we can use it to set up our walker and make its gait more human-like. We can achieve that by adjusting the position of the foot switches and in effect changing the times at which the knees are released. The moment at which the knees are released is critical, and can affect the whole walking cycle.

It is important to clarify that humans do not physically lock their knees as our mechanical walker does, but according to the inverted pendulum analogy that we used in order to describe the gait of a person, the stance leg is kept relatively straight during the single support phase and that allows us to treat this phase as if the knee is locked. Therefore, for simplicity we will use the term locked knee for both the test person and the walker.

For the human comparison, a person walked on the same ramp we used in the afore-mentioned experiments. The subject walked in his normal gait and took about five to seven steps down the ramp with visual markers, shown in Fig. 9, attached to his hip, knees, heels, and toes for easier measuring of the time intervals. During each walk, we recorded a video from a perpendicular angle. After we completed about twenty experiments, we calculated the average times within one cycle. We decided for the purpose of our experiment, that one cycle would start at the moment when the heel of the right foot strikes the ramp (ground) and ends the next time that the right heel strikes the ramp. Within that cycle we measured the moments of locking the left and the right knees, the moments of releasing (unlocking) the left and the right knees, the moments of lifting the left and the right foot, and the moments when left and right heels strike the ramp. After we performed all the necessary calculations with our test subject we performed exactly the same experiment under the same conditions as before with our walker. We took a video and calculated the same time intervals, where the right leg of the test subject corresponds to the inner leg of our walker and the left leg of the test subject – to the outer leg of the walker respectively.

Table I shows the times for all of the measured moments relative to the beginning of the cycle for both the test subject and the walker. Fig.10 shows a picture sequence of the test subject, where one through six are moments of right heel strike; left foot lift; left foot swing phase; left heel strike; right foot lift and right heel strike respectively. Fig.11 shows a picture sequence of the walker, where one through six are moments of inner heels strike; outer feet lift; outer feet swing phase; outer heels strike; inner feet lift and inner heels strike respectively. Fig. 12 shows one graphical comparison between the human walking cycle and the walking cycle of our walker. It is obvious, that except for some noticeable difference (dashed-line ellipse) between the moments when the test subject and walker lift their legs, the walking cycles of both are very close in terms of timing and intervals between different walking stages. Even though there are some fluctuations in the experimental results, we can conclude that under the same conditions the test subject's walking cycle times and the times of the walking cycle of our walker are quite similar to each other in the trials that we performed. This characteristic leads us to speculate that the average values are suitable enough and can be used in the process of adjusting our walker and making its gait appear as human-like as possible, considering its design features.

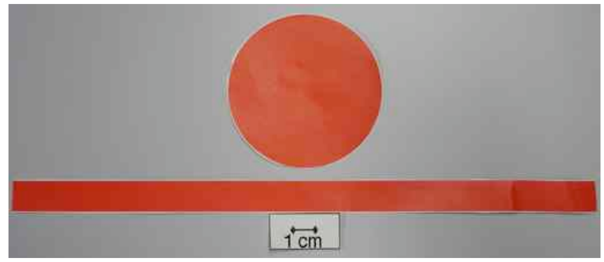

Fig. 9. Circular and Linear Visual Markers.
Circular markers are attached to hip, knees, heels and toes and the linear markers are attached to the thighs and shanks.

TABLE I
TIME INTERVALS COMPARISON OF THE TWO WALKING CYCLES

Human	Average	Average	Walker
Right heel: strike, s	0	0	Inner heels: strike, s
Left knee: release, s	0.05	0.04	Outer knees: release, s
Left foot: lift, s	0.21	0.07	Outer feet: lift, s
Left knee: lock, s	0.61	0.57	Outer knees: lock, s
Left heel: strike, s	0.67	0.65	Outer heels: strike, s
Right knee: release, s	0.73	0.68	Inner knees: release, s
Right foot: lift, s	0.88	0.73	Inner feet: lift, s
Right knee: lock, s	1.30	1.20	Inner knees: lock, s
Right heel: strike, s	1.38	1.31	Inner heels: strike, s

All units are seconds.

Fig. 10. Picture Sequence of a Walking Cycle of the Test Subject.
1-right heel strike, 2-left foot lift, 3-left foot swing phase, 4-left heel strike, 5-right foot lift, 6-right heel strike.

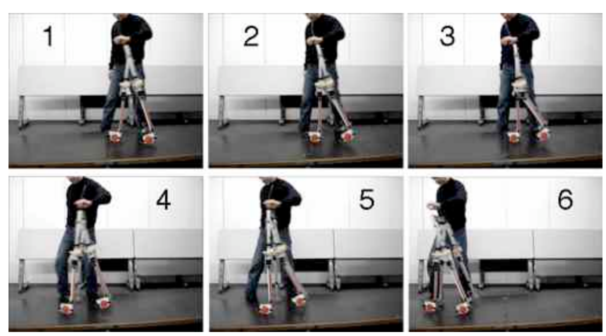

Fig. 11. Picture Sequence of a Walking Cycle of the Walker.
1-inner heels strike, 2-outer feet lift, 3-outer feet swing phase, 4-outer heels strike, 5-inner feet lift, 6-inner heels strike.

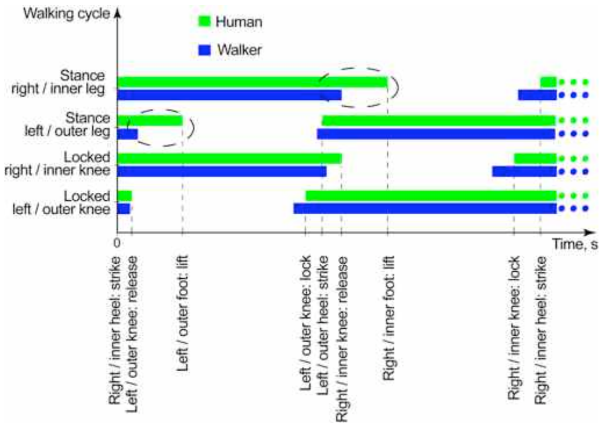

Fig. 12. Walking Cycle Comparison.
While the horizontal bar is present, for example, while the top green bar is present the right leg is the stance leg and while it is not, the right leg is the swing leg

IV. Conclusion

Our improved design of the knee-locking mechanism with active release shows promising results in the experiments. Even though we observed some variation of the number of successful trials, it is obvious, that although not entirely passive the new knee-locking mechanism is more efficient in terms of the walker managing to walk the entire length of the ramp and also compared with the previous design based on the entirely passive, magnetic lock. It helps the walker achieve longer and more stable walks. It is more robust and reliable. We performed several sets of a hundred trials and managed to achieve an average of forty-four successes. Using the proposed design we were also able to obtain a more even distribution between trials of five, six, and seven step walks achieved by the walker. The experimental results show that the walker, equipped with the new knee-locking mechanism makes five or more steps in much higher percentage of the trials. Also the unsuccessful trials were greatly reduced.

In our research experiments about the walker and the human walking cycles, we measured time intervals between moments of the movement we determined to be important. We organized these results and created a graphical representation of the walking cycle in a form that can provide utility when we compare them to each other, and use the results of this comparison in the process of adjusting our walker and making its gait appear as human-like as possible.

In terms of design, we plan on researching the possibility of developing a launching mechanism for our walker in order to reduce the irregularities caused by the human-dependent start of the walker's operation. Another priority is adding power to the hip as a next step towards realizing walking on level surfaces.

In terms of setting up our walker, we plan on using the acquired data from the human walking cycle in order to make the gait of the walker as close as possible to the human one. This might prove to be difficult, because of the higher complexity and adjustability of the human body, but we believe that there is place for improvements of the walker's gait. Currently, analysis is under way to determine to what extend the two gaits match and which stage of the walking cycle of our machine must be adjusted to make its gait more human-like.

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