Active Knee-release Mechanism for Passive-dynamic Walking Machines

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1. Introduction

In this chapter we will present the design and development of two knee mechanisms. One uses permanent magnets to lock the knee in its extended position and the other features an active mechanism for releasing the passively locked knee. We will also present a comparison between the experimental results achieved with each of the two knee mechanisms.
One of the big, and still unsolved, problems in 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 approach are that it results in a non-efficient gait in terms of energy consumption (Collins et al., 2005), it requires complex controllers and programming, and this strategy often results in gaits that are unnatural when compared to the human gait. Second is a somewhat new strategy called passive-dynamic walking, introduced by Tad McGeer (McGeer 1990) in the late 80's, early 90's. A walker based on the 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 the impact of the feet on the ground and friction. The advantages of passive-dynamic walking are high-energy efficiency, simple or no control, and a 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 walkers to include actuators that supply the necessary power instead of gravity (Collins and Ruina, 2005; Wisse and Frankenhuyzen, 2003; Wisse, 2004). This enables them to walk not only downhill, but on level and uphill surfaces as well. This possibility greatly increases the prospects for practical application.
The knee mechanism is a major part in passive-dynamic walkers. There are several different designs that have been implemented in walkers up to now. The original walker built by McGeer uses a mechanism with suction cups that keeps the knee extended as shown in Figure 1. The drawback of the suction cups design is that it is difficult to set up and not very efficient.

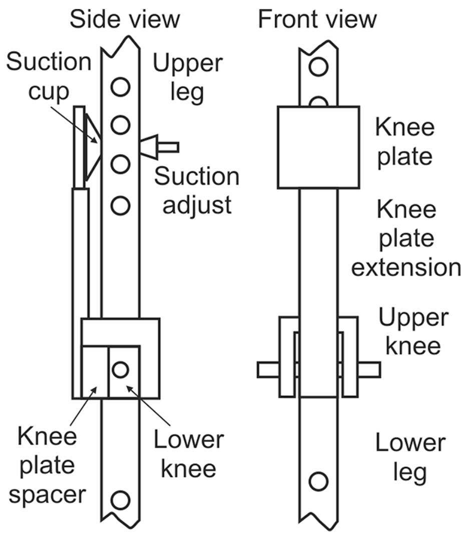

Fig. 1. Knee design with suction cups knee-locking.

Another popular design is used in the University of Delft's Mike (Wisse and Frankenhuyzen, 2003) and subsequent walkers Max and Denise (Wisse, 2004). The locking of the knee is achieved actively by McKibben muscles, which are counteracted by weak springs as shown in Fig.2. As a drawback we can mention that the McKibben muscles are not linear, and require controller that takes this feature into account. They also require a source of air.

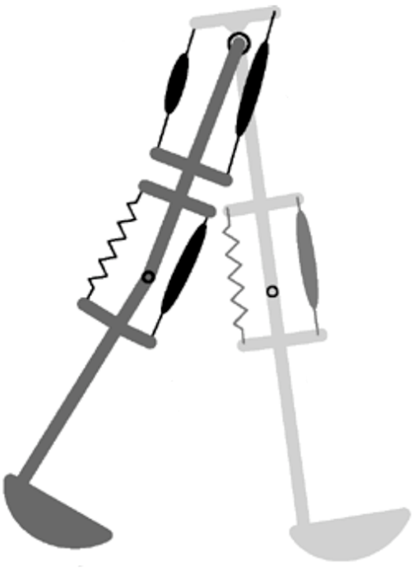

Fig. 2. Knee design with McKibben muscles knee-locking.

A third popular knee design is implemented in the Cornell powered biped (3). It features an electromagnetic release system shown in Fig.3, where (A), (B), (C), (D), (E), (F), (G) and (H) are a latch arm, a roller, a shank, a hinge, a shaft, a latch surface, a thigh and a solenoid, respectively. This design is robust and easy to control, but it is comprised of many parts, which makes it quite complicated. A similar design, where an electromagnetic clutch is used to engage or disengage a knee motor is developed by Baines (Baines, 2005).

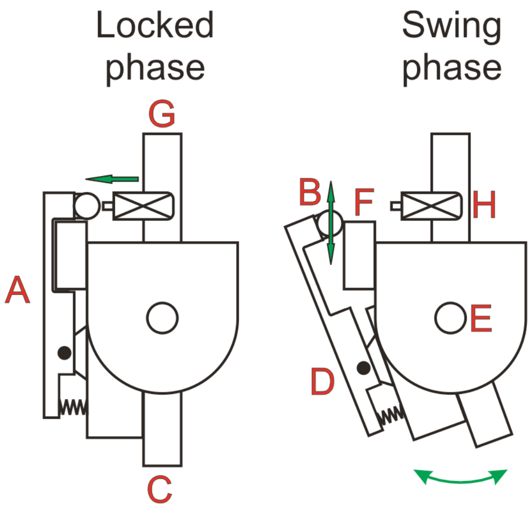

Fig. 3. Knee design with electromagnetic knee-release.

We developed our two knee locking mechanism with simplicity in mind. We wanted to understand if it was possible to develop a passive walker and a knee mechanism specifically based only on observation and experimentation without any modeling and simulations. A detailed model describing the mechanisms of generation and stabilization of a fixed point of passive walking, as well as leg-swing motion analysis of a passive-dynamic walker can be found in the research done by Prof. Sano's team at the Nagoya Institute of Technology (Ikemata et al., 2007), (Ikemata et al., 2008). Our aim was to build a mechanism that is simple, robust, and easy to use and set up. The purposes of this chapter are to present the mechanical design of the two knee mechanisms, to introduce the achieved experimental results, to make a comparison between them, and to discuss their effectiveness.

2. Knee Mechanism with Permanent Magnets

The dynamics of passive-dynamic walkers cause the swinging leg to bend and extend on its own. However, in order to achieve a stable gait, the knee must be able to swing with minimal friction, meaning minimal energy loss. Taking this into consideration, the most logical choice for the knee joint is a ball bearing. Additionally, the knee must be equipped with a knee-locking mechanism that supports the knee during its extended phase and prevents it from bending while bearing the weight of the walker.
For our walker, the knee is cut from an aluminum block and is comprised of only an upper knee, to which the aluminum lower leg is attached directly through a shaft and a pair of ball

bearings (Trifonov and Hashimoto, 2006). For the locking mechanism, we are using a knee plate spacer and a knee plate, cut from acrylic, as with the original McGeer design, but we decided to try a new approach by using magnets instead of a suction cup. We adjust the locking magnetic force by changing the distance between the magnet(s) and the steel plate. This can be achieved either by using magnets with different sizes or by using a different number of magnets. The smaller the distance is, the stronger the force. Another advantage of the magnetic lock is that it does not require physical contact between the locking parts (magnet and steel plate). In this way the material wear is reduced and the lock can be used longer without having to worry about replacing some of its parts. 3D renderings are shown in Fig. 4, where (A) is knee, (B) is knee plate, (C) is magnet(s), and (D) is a steel plate. A drawing of the knee mechanism with some main dimensions is shown in Fig. 5.

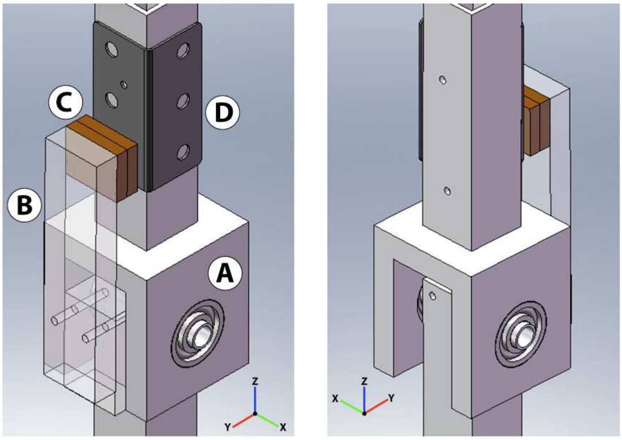

Fig. 4. 3D renderings of the knee mechanism with permanent magnets.

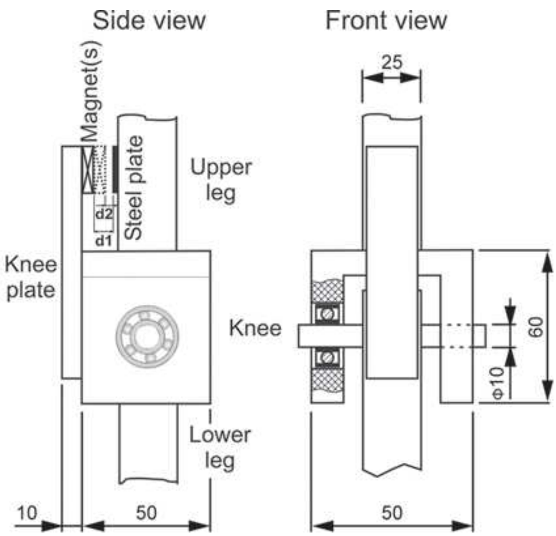

Fig. 5. Drawing of the knee mechanism with permanent magnets.

3. Knee Mechanism with an Active Release System

We designed a second newer, simpler, and lower in weight knee-locking mechanism (Trifonov and Hashimoto, 2007). 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. 6 and Fig. 7. Additionally, there is a switch attached to each foot of the walker, which is used to control the DC motor, but is not shown in the figure. The entire knee mechanism was designed in 3D modeling software and cut on a CAM machine. 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.

An active release system has been implemented before on a passive-dynamic walker. The Cornell powered biped (Collins and Ruina, 2005) uses an electromagnetic solenoid for the release of the passively locked knee mechanism. The advantages of our system are the much simpler design and the absence of a controller.

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, lifting it. After the locking axle passes under the hook, it comes back down to lock the axle, effectively locking the knee itself. The locking hook is balanced by a counter weight in such a way that it comes back down 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 the ON position, thus turning on the power for the DC motor. This causes the motor to lift the locking hook and release the knee. Immediately after the leg lifts off the ground and starts swinging, the foot switch returns to the OFF position, cutting the power, and the locking hook returns to its initial position. The foot switch is mounted to the side of the foot plate, such that it does not influence the walking of the machine.

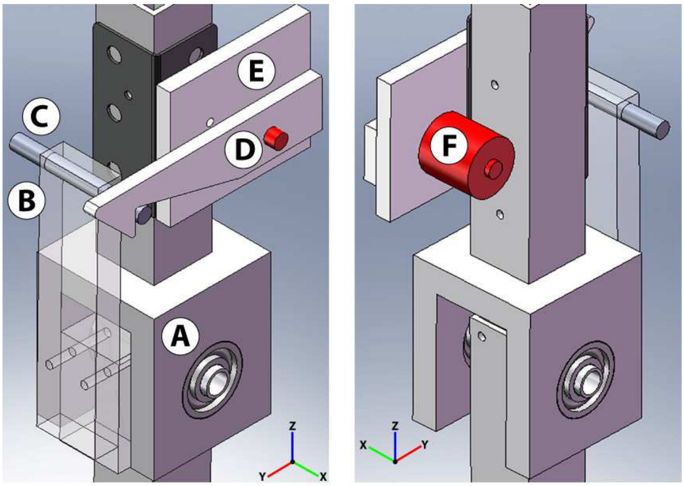

Fig. 6. 3D renderings of the knee mechanism with an active release.

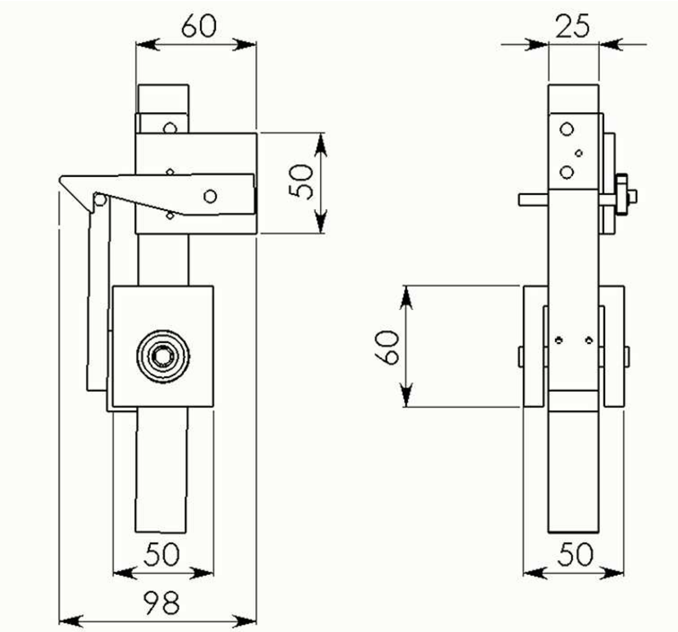

Fig. 7. Drawing of the knee mechanism with an active release.

4. Experiments and Results

To compare the two knee mechanisms, experiments were conducted with the same walker shown in Fig. 8, built from square aluminum tubes for the legs and 2mm thick steel plate for the feet (Trifonov and Hashimoto, 2006). For the thighs and lower legs, we used 2.5 by 2.5cm square aluminum tubes with lengths of 34 and 43.5cm respectively. The total height of the walker is 89cm and the radius of the feet is 12.3cm. The total weight is 4.5kg. The knees were outfitted first with the magnetic system and then with the active release one. The walker was set on a ramp, which measures 3m in length, 90cm in width, and has a 3° grade relative to the ground. The ramp is covered with a rubber mat to reduce the chance of foot slippage.

We performed several sets of a hundred trials (walks) down the ramp for both knee 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. 9 shows a comparison between the two knee mechanism designs in terms of average number of steps made in each of the hundred trials.

As the results show, using the knee 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, using the active mechanism produces fewer failures than the magnetic one.

Fig. 8. Walker on the ramp, outfitted with knees with active release system.

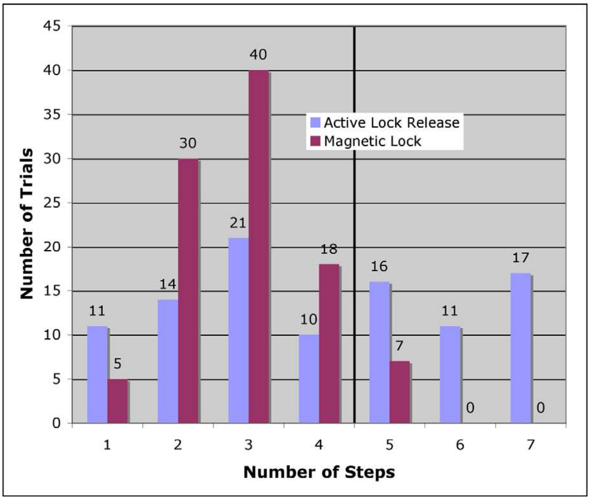

Fig. 9. Comparison between the experimental results achieved with the two mechanisms.

There are several types of reasons for a failed trial in general. One is an incorrect start of the walker by the person performing the experiments. As this is done manually, it is subjective and depends on the experience of the starter. In case of an incorrect start the walker fails on the first or the second step of the walk. If the walker is started correctly and goes beyond the first couple of steps it enters a stable gait and from this moment onwards there are two other possible reasons for failure, which may occur at any time. One is slippage of the foot against the slope, which may be attributed to dirt or other obstacles present on it. Another is failure to lock or unlock the knee. Failure to lock the knee is usually caused by the so-called knee bouncing. That is, when the knee extends too fast, the knee plate bounces off the knee, and the locking hook has no time to lock it in place. We have tried to reduce this to a minimum by adding a small 1mm rubber mat to the knee face to cushion the hit. Failure to unlock the knee is mainly due to a late attempt to do it. If the foot switch activates the DC motor after the time when the knee starts to bend, the locking axle is already applying pressure to the locking hook and it is unable to lift and release the knee. By adjusting the foot switch to activate earlier in the walking cycle we have significantly reduced the occurrence of this problem.

5. Discussion

In this chapter we presented two knee mechanism designs. One features a permanent magnet locking system and the other an active release system. We performed a series of experiments with both mechanisms mounted on the same passive-dynamic walking machine and compared the results we achieved.

The first knee mechanism was based on permanent magnets. We speculated that changing the distance between a permanent magnet and a steel plate, and hence changing the magnetic force, would be sufficient to control the release moment of the knee with this passive magnetic mechanism. The experiments showed that the walker using this mechanism was never able to make more than five steps and was only able to make a successful trial, as defined earlier in the paper, in seven out of a hundred attempts. As a result of what we observed in several sets of experiments we have reached the conclusion that it was very difficult to precisely setup and reliably uses the machine in the configuration with the magnetic knee mechanism. Ultimately, we decided to design and build a completely different mechanism, with actively powered knee release action, which is much simpler and more robust.

Our design of the knee mechanism with active release showed 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 mechanism is more efficient in terms of the walker managing to walk the entire length of the ramp when compared with the previous design based on the entirely passive, magnetic lock. The active release approach allows the walker to achieve longer, more stable walks and 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 a higher percentage of the trials. Also the unsuccessful trials were greatly reduced.

Our goal from the start of this research was to prove that it is possible to design a simple and usable passive-dynamic walker without any complex modeling and simulations. We wanted to see if the trial and error method would work for passive-dynamic walking where the stability range of the actual machines is very narrow. The results show clearly that there is an obvious improvement going from the first design to the second one. This means that if the work continues in the same way additional improvement is possible.

Our plans for the future include adding active control of the knee release system and building a starting mechanism for the walker in order to be able to control the release moment precisely and to reduce the failure rate even further. We are already working on adding a controller and hip motor to the walker. Our goal is set on achieving a highly successful walk on the experimental ramp and eventually on a flat surface.

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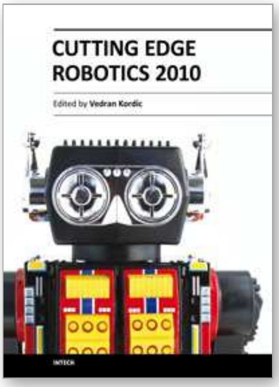

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