Design Issues and Applications for a Passive-Dynamic Walker

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Abstract

Humanoid and walking robots have been widely developed and their use in human environments is not far out of reach. The main problems in practical applications of machine walking are energy consumption, complex control and design, and high cost. The main feasible indoor application of a walking machine is that of a humanoid robot as a companion, nurse, guide, or information desk or reception clerk. In a smart object system environment, such as a smart house where all objects are interconnected, a humanoid robot can provide services for the centralized host or gateway server of the house. It is a mobile system already equipped with sensors, controllers, manipulators (hands) and a communication system. From the features of humanoid robots and of the smart object systems, a new direction of research could emerge embracing parts of both fields. In the interest of furthering the capabilities of walking robots, we designed an approach to further the capability of walking robots. 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 in terms of dynamics. We conducted our experiments with two different knee designs. Both mechanisms were designed in an attempt to create a simpler and easier-to-adjust knee-locking mechanism. We conducted a series of experiments in which we counted the steps the walker made while walking down an incline and compared the results achieved with the two different knee-locking mechanisms. We also performed a walking cycle investigation of a person walking casually down the same slope used for the walker experiments, calculated the average time intervals within one cycle and made a comparison between the test subject and our walker.

Keywords: *Passive-Dynamic Walker, Walking machines, Knee design*

1. Introduction

The most common goals pursued in machine walking besides the development of humanoid robots are related to human welfare and ability augmentation. Human welfare applications may consist of partial or complete prosthetic solutions such as Victhom’s bionic leg [1] or walking chairs as is the case with Waseda University’s WL-16 [2] for providing the ability to climb stairs and go over obstacles to the disabled. Ability augmentation is most commonly associated with the development of exoskeletons for increased body strength [3], for rehabilitation, or for increasing movement range of people with impaired motion abilities.

Humanoid and walking robots have been widely developed and their use in human environments is not far out of reach. The main problems in practical applications of machine walking are energy consumption, complex control and design, and high cost. Generally, outdoor applications are the feasible choice for walking machines. They are better suited to traverse rough terrains and in many places where roads or smooth surfaces are not available they are the only possible option.

Currently, smart chairs, tables, office equipment and electrical appliances are in use or are being developed for indoor use. Using legs instead of wheels for this kind of applications is unpractical, for several reasons. First, the surface of indoor facilities such as offices, homes and public buildings is even and wheels are perfectly capable of handling it. Second, wheels are a cheaper solution to implement in terms of implementation and maintenance costs. Third, wheels are easier to implement from design and technical point of view. The main feasible indoor application of a walking machine is that of a humanoid robot as a companion, nurse, guide, or information desk or reception clerk. All of these are cases, where from psychological point of view, a customer or a patient might prefer a more human-like appearance.

In order to expand the indoor application of the humanoid robots we can mix the aforementioned applications with some features typical of the smart object systems field. Let us consider the following scenario. We have a smart home where most objects are interconnected. There is a need for a gateway server that monitors user and environment context information in order to provide proactive services. For example, two people are discussing a topic in a room with some music playing in the background. The discussion becomes more serious and the role of the gateway in this situation should be to recognize this change and, for example, lower the volume of the music. To implement this and other example scenarios, there is a need for sensors and devices that act according to the commands from the server. The sensors are usually built-in the environment, walls, furniture, and electrical appliances. The effectors are usually integrated in furniture or appliances. In some cases, this distribution of the parts of the smart system is necessary, for example in smart chairs or tables, in which the sensing and the acting part must be inside and the server could be the centralized server of the smart house. In other cases though, it is much better to have the sensing and acting part of the system be mobile. This is where the humanoid robots and smart object systems' paths could intersect. A humanoid robot already has sensors, controller and manipulators on it. It is mobile and can follow the human around the house. This will reduce the necessary number of sensors for one, hence the cost. A humanoid robot also has a communication system already installed and can be connected to all smart objects in the house and act as the gateway server for all services.

One of the big, and still unsolved, problems in humanoid 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 [4], 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 [5] in the late 80's, early 90's. His main inspiration came from walking toys created earlier [6], which use the same principle. 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 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 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 walkers to include actuators that supply the necessary power instead of gravity [7, 8]. This enables them to walk not only downhill, but on level and uphill surfaces as well. This possibility greatly increases the prospects of practical application. Some passive and powered walkers based on passive dynamics are shown in Figure 1.

Figure 1. Some passive and active walking machines
(left to right): copy of McGeer's original design; The Cornell Passive Biped With Arms; The Cornell Biped; The TU Delft Biped

They have been developed by the teams of Andy Ruina of Cornell University [4, 9], Steven Collins of University of Michigan [10, 11] and the Bio-robotics Lab at the Technical University of Delft [8, 12, 13]. All of these walkers are functional and have proven more or less effective, but they are all quite complex. The walking machine that we designed and built is simpler and easier to set up and use. Our approach focuses on building a machine without any complex modeling and design. We realize an idea based on real world observations and test its feasibility through experiments. After assessing its effectiveness we improved the design of our machine.

In this paper we will present the development of our walker (section 2), including two knee designs that we have developed: magnetic knee-locking mechanism and active knee-locking mechanism. We will also present a comparison of the experimental results achieved with each of the two knee-locking mechanisms (section 3), and a comparison of the walking cycles of the walker and a human test subject (section 4). We will be discussing the achieved results and difficulties encountered in the experiments.

2. Design issues and decisions concerning our walker

In this chapter we will introduce the mechanical design features of our passive-dynamic walker [14] in Figure 2, based on the original two-dimensional walker with knees by McGeer, and make a comparison to the original design, speculating on some advantages and disadvantages of both.

Figure 2. Our four-legged walker with active knee-locking mechanism

When talking about the design of passive-dynamic walking machines, there are several key features to be considered: the number of legs (two or four legs coupled two by two), hip design, foot design, knee design, and the knee-locking mechanism.

2.1. Two or four legs

There are two popular design paradigms for passive-dynamic walkers. One has four legs coupled two by two, forming an inner and outer leg, effectively acting as a bipedal mechanism in terms of dynamics. The other design has two legs, much like a human. The latter design concept is more human-like than it's predecessor, and has been more widely used in recent years. However, it has the disadvantage that these types of machines must deal with a two-legged walkers' tendency to turn and sometimes fall to the side. Adding counterweighted hands is most commonly used to reduce this tendency. The design with four legs has higher lateral stability, but is less human-like in appearance.

We decided to build a four-legged walker for this extra stability, allowing us to test the design improvements made without stability concerns. As this is the first passive-dynamic walker that we have built, and it was to be used as reference for subsequent versions and designs of other walkers, we decided to build a machine, Figure 2, which resembled the original four-legged design with knees created by McGeer [15] as closely as possible. The changes that were made were only slight design improvements and innovations to increase efficiency or simplicity.

2.2. Hip Design

There are a few considerations to keep in mind during hip design, the most important of which is to ensure the friction in the hip joint is as low as possible. For this to be achieved, the best choice for the coupling element is a ball bearing. It has very low friction and is readily available in various sizes in most hardware shops.

The original hip design uses hip plugs that are machine-cut from an aluminum block and then hard pressed into the thigh and bolted to the hip bar, as shown in Figure 3. These plugs are used to hold the bearings to the shaft connecting the outer and inner legs. In our opinion, the cutting of the plugs is too complex. It requires 3D design and high precision to match the sizes of the plugs and the thighs. For our walker, we circumvent this problem with an external bearing holder, bolted to the side of the thigh, which is cut from acrylic plate by an easy to use engraving plotter. Figure 3 also shows our bearing mount approach.

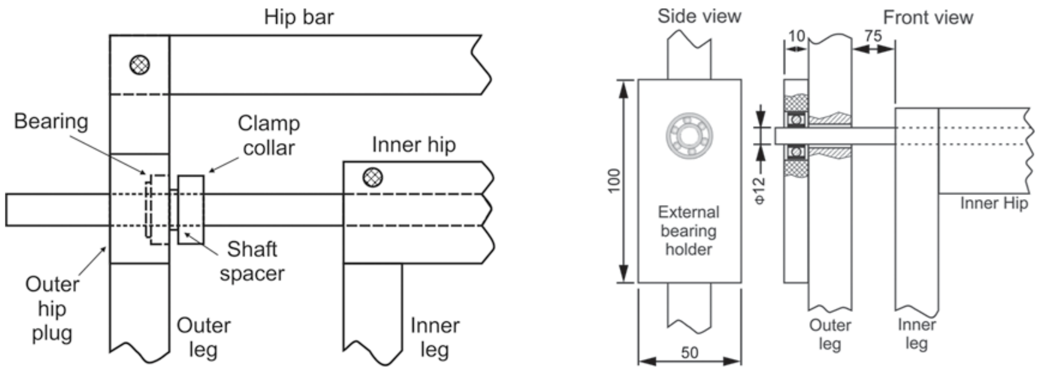

Figure 3. Original McGeer Hip Design as Presented by M. Garcia [16] (left) and Our Approach (right)

Another advantage of the external bearing holder is that it is very easy to assemble and disassemble, which allows us to easily change the upper legs with legs of different sizes and shapes if we so choose.

2.3. Foot Design

In order to minimize the energy losses from the inelastic impact of the feet on the ground, the feet must be as close to each other as possible [17]. In this way, the transition between each step will be smoother and the energy loss minimized. However, placing the feet close together reduces the lateral stability of the machine, which is usually increased by placing them further apart. In four-legged machines the lateral stability is improved by the design itself, but in a two-legged machine this is a very important concern.

In the original McGeer design of the foot, shown in Figure 4, the foot plate is attached to the lower leg (shank) by a foot holder, which is again machine-cut from an aluminum block. Although it secures the foot firmly and directly below the leg, a drawback is that it has to be cut with high precision and in general it is not necessary for the foot to be attached directly below the leg, as long as the foot plates are attached symmetrically to the four legs to keep the weight distribution symmetrical. This is why, to simplify the construction, we decided to do away with this part altogether, Figure 4, and attach the foot plate to the lower leg without a foot holder.

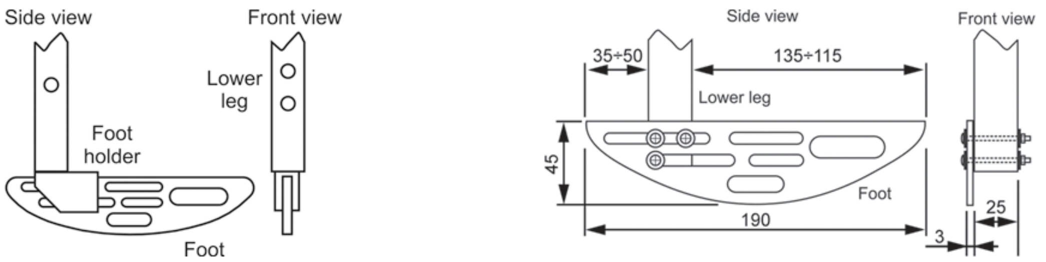

Figure 4. Original McGeer foot design (left) and foot design of our walker (right)

The foot plate itself has the same design and shape as the original one, it has been cut from an aluminum plate and is mounted on the lower leg in a way that allows us to make slight adjustments in its position.

2.4. Knee Design

The dynamics of passive-dynamic walkers cause the swinging leg to bend and extend on its own. In order to achieve a stable gait, the knee must be able to swing with minimal friction, meaning minimal energy loss. 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.

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. The drawback of the suction cups design is that it is difficult to set up and not very efficient.

Another popular design is used in the University of Delft's Mike [8] and subsequent walkers Max and Denise [13]. The locking of the knee is achieved actively by McKibben muscles, which are counteracted by weak springs. As a drawback we can mention that the McKibben muscles are not linear, and require a controller that takes this feature into account. They also require a source of air.

A third popular knee design is implemented in the Cornell powered biped [7]. It features an electromagnetic release system. 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 presented in [17].

We developed our two knee locking mechanisms with simplicity in mind. Our aim was to build a mechanism that is simple, robust, and easy to use and set up. Initially, we built an entirely passive knee locking mechanism and ran our experiments with it mounted on our walker. After that we determined that we needed to make some design improvements to increase its stability and reliability. Thus, we developed a newer knee mechanism with an active release system.

2.4.1. Knee mechanism with permanent magnets: 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 [14]. 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 a 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 Figure 5, 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 Figure 6.

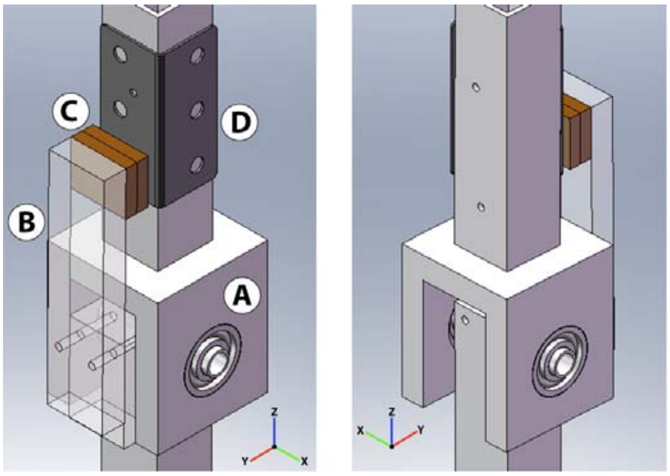

Figure 5. 3D renderings of the knee mechanism with permanent magnets

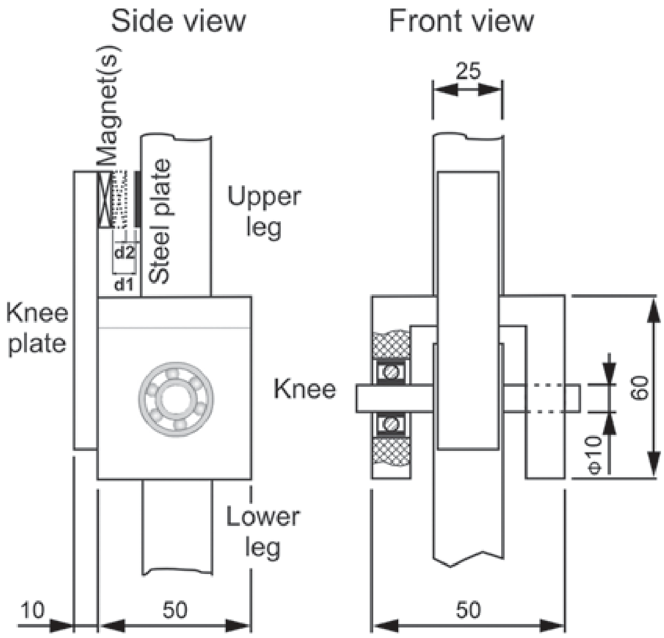

Figure 6. Drawing of the knee mechanism with permanent magnets

2.4.2. Knee mechanism with an active release system: We designed a second newer, simpler, and lower-in-weight knee-locking mechanism [18]. 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 Figure 7 and Figure 8. 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.

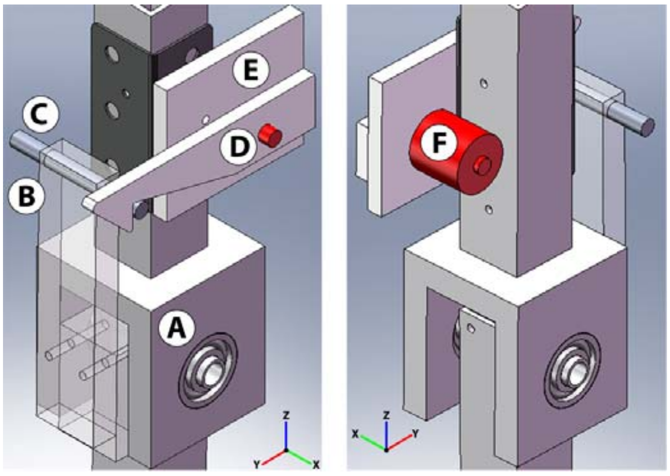

Figure 7. 3D renderings of the knee mechanism with an active release

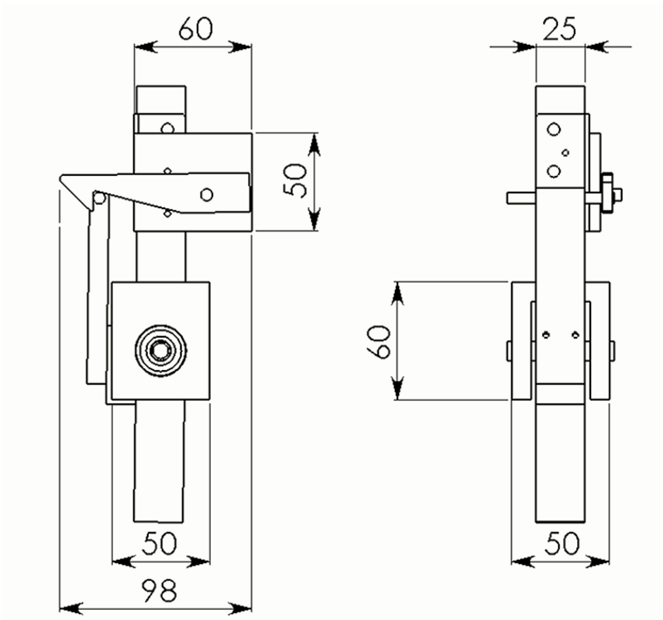

Figure 8. Drawing of the knee mechanism with an active release

An active release system has been implemented before on a passive-dynamic walker. The Cornell powered biped [7] 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.

3. Knee design evaluation

The only difference between the two configurations of the walker is the knee design. That is why we assume, that performing the same tests in the same environment and with the same person to start the machine on the slope would provide us with useful information about the effectiveness of the knees. We decided to use the number of steps made as an evaluation criteria. To compare the two knee mechanisms, experiments were conducted with the same walker shown in Figure 2, built from square aluminum tubes for the legs and 2mm thick steel plate for the feet [14]. 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. Figure 9 shows a comparison between the two knee mechanism designs in terms of average number of steps made in each of the hundred trials. The successful trials are represented on the right side of the black vertical line.

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.

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.

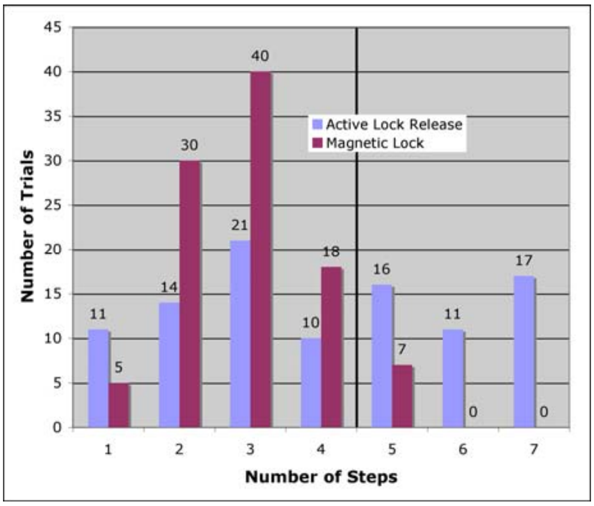

Figure 9. Comparison between the experimental results achieved with the two mechanisms

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 what is sometimes referred to as 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.

4. Walking cycle research and comparison

4.1. Related work

There are two main theories that are widely accepted in the study of walking: the six determinants of gait and the inverted pendulum theory (Figure 10a & b) [19]. 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 while disproving the other. The six determinants of gait have been accepted as fact for fifty years without being subjected to experimental testing [19]. A simple approach, which also provides easy prediction of the results, should be used to find out which theory is more sensible.

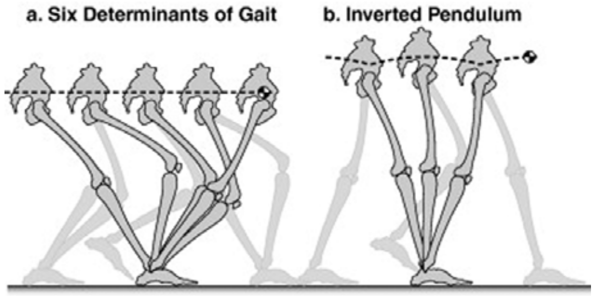

Figure 10. Walking theories [19]
(a) – Six determinants of gait; (b) – Inverted pendulum

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 view feature 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 [19], 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.

4.2. Human and walker cycle comparison

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 does one cycle take? 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 compare our walker's gait to that of a person.

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-walker comparison, a person walked on the same ramp we used in the afore-mentioned experiments [20]. The subject walked in his normal gait and took about five to seven steps down the ramp with visual markers, shown in Figure 11, 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, releasing (unlocking) the left and the right knees, lifting the left and the right foot, and 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.

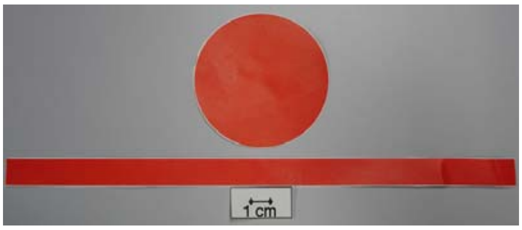

Figure 11. Circular and linear visual markers
Circular markers are attached to hip, knees, heels and toes and the linear markers are attached to the thighs and shanks

Table I shows the times for all of the measured moments relative to the beginning of the cycle for both the test subject and the walker. Figure12 shows a picture sequence of the test subject, where one through six are moments of right heel strike; left foot lift; left leg swing phase; left heel strike; right foot lift and right heel strike respectively. Figure13 shows a picture sequence of the walker, where one through six are moments of inner heels strike; outer feet lift; outer legs swing phase; outer heels strike; inner feet lift and inner heels strike respectively. Figure 14 shows one graphical comparison between the human walking cycle and the walking cycle of our walker. It is obvious, that except for one 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.

Table 1. 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

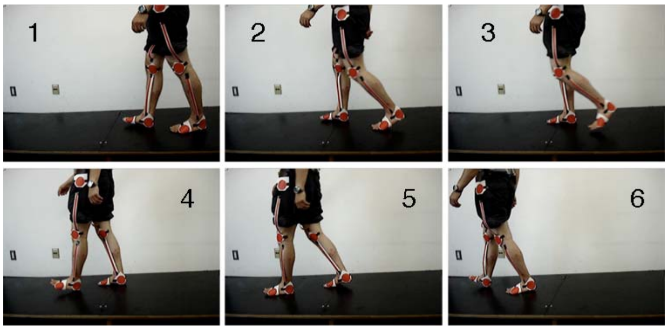

Figure 12. Picture sequence of a walking cycle of the test subject
1-right heel strike, 2-left foot lift, 3-left foot swing phase, 4-left heel strike, 5-right foot lift, 6-right heel strike

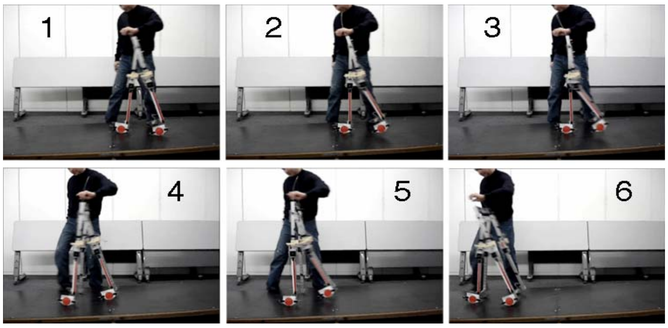

Figure 13. Picture sequence of a walking cycle of the walker
1-inner heels strike, 2-outer feet lift, 3-outer feet swing phase, 4-outer heels strike, 5-inner feet lift, 6-inner heels strike

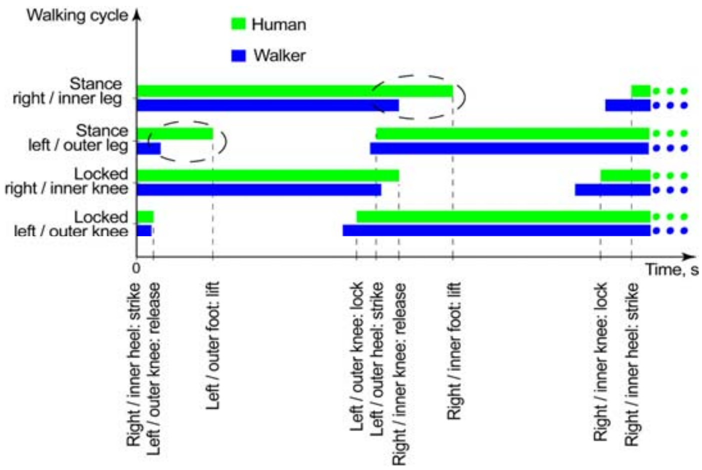

Figure 14. Walking Cycle Comparison
While the horizontal bar is present, for example, while the top green bar is present the right leg is the stance leg and while it is not, the right leg is the swing leg

The difference between the walker and the human is due to the specific design restrictions of the walker. The knee release should be done just after the swing leg touches the ground, as it is done in human walking, but in practice this is difficult to achieve and coordinate precisely, which is why the release occurs just before that moment in the walker.

Even though there are some fluctuations in the experimental results, we can see that under the same conditions, the walking cycle times of the test subject and of the our walker are similar to each other in the trials that we performed.

5. Discussion

5.1. Knee design evaluation

The first knee mechanism that we design was based on permanent magnets. We speculated that changing the distance between a permanent magnet and a steel plate, thereby 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 reached the conclusion that a machine utilizing a magnetic knee mechanism is very difficult to setup precisely and use reliably. 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 active release knee mechanism showed promising results in the experiments. Even though we observed some variation in 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 this knee-locking mechanism makes five or more steps in a higher percentage of the trials.

5.2. Walking cycle research

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. Human-like appearance has a very high psychological importance when it comes to human-machine interaction. People are more likely to trust or engage into any kind of interaction with a humanoid robot if it resembles a human more closely in all aspects, including gait.

We ran into several difficulties, which need to be addressed in order to make the experiments more accurate and reliable. A regular camera’s frame rate may prove to be insufficient. Time intervals between some moments of the walking cycle are small and a high frame rate camera will provide for a better time measuring accuracy. In experiments with the walker, a human operator starts it manually. This leads to failed trials due to unsuccessful start. This type of failures accounts for about two-thirds of all failures. Their percentage is reduced with the experience gained by the operator, but a starting stand that eliminates him altogether should decrease the failure rate even further. When started, the walker needs two to three steps to settle into a steady gait. This has to be taken into consideration when selecting the cycle to be measured. The test subject has to be chosen to have the same or very similar dimensions as the walker so that the comparison between the measured times is possible. And last, many trials of the test subject have to be measured and averaged or many test subjects have to be used in order to increase the reliability and the accuracy of the gathered results, as the gait of every person is slightly different.

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