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Design, development and testing of a lightweight and compact locking mechanism for a passive knee prosthesis.

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***Abstract*— In knee prosthetics and orthotics, there is the need to have a change in stiffness within the gait cycle. Doing this using a locking mechanism requires locking high forces using a small amount of energy. This paper presents a novel compact and light-weight locking mechanism which combines a ratchet-and-pawl and a singular position locking mechanism. It is used as a lock in a passive knee prosthesis and allows a change in compliance of the joint. The mechanism is transparent during the swing phase, allowing the joint to flex, and during the weight acceptance phase it provides the same stiffness as a natural knee joint. It is explained that this high stiffness characteristic can be approximated by a linear spring put in parallel with the knee joint. The mechanism uses a small servo motor to unlock the ratchet, other than this the operation is fully passive. The prosthesis has been tested during walking tests with amputee test subjects. The passive knee prosthesis is part of the CYBERLEGs-Project.**

I. Introduction

Locking mechanisms are required in prosthetics and orthotics, and in general robotics applications where there is the need to store and release energy as desired or to fix joints or actuators in a certain position. The characteristics of the locking mechanism can vary in many different aspects for each of these applications, depending on the boundary conditions of the posed problem: forces on the mechanism, limitations in size or weight, locking in one or more directions, single or multiple positions where the mechanism can be locked, or in some cases the locking must be possible at any position. The importance of these conditions will determine the type of locking mechanism that is most suitable.

The locking mechanisms can be categorized based on their working principle: mechanisms using a mechanical stop, a singularity, friction or hydraulic damping.

There are locking mechanisms that use a mechanical stop to inhibit the movement of an object in a certain direction. An example of this kind of mechanism is a ratchet and pawl, where the pawl fits in an excavation on the ratchet and because of this it is able to prevent the ratchet from rotating in one direction. Ratchets and pawls come in many different shapes and sizes. Examples of the use of this kind of mechanism can be found in most early prosthetic and orthotic devices, but also in modern commercial devices, where the rotation of the knee joint would be either completely locked during the whole step or only during the stance phase. This the case in the Otto Bock FreeWalk [1]. Examples of ankle joints using a ratchet are [2] and the AMPFoot 1 [3]. When considering the design of this kind of mechanism, there will be a trade-off between strength and accuracy. A higher locking force will require larger tooth, which reduces the number of possible locking positions for the same diameter of ratchet.

The locking can be done using the properties of a singular position of a mechanism. A mechanical singular position can be described as the position of a mechanism where one or more physical quantities will go towards infinity. In the case of a lock we want the transmission ratio between an applied force and the outcome movement to become infinite, meaning no matter how high the force in a certain direction will be, there will be no movement in that direction. On the other hand, as the name suggests, this locking will only happen in this specific position and in any other position the movement will not be hindered. An example of such a mechanism is the four-bar linkage used in the AMP-Foot 2 [4]. A small motor stores energy in a spring pushing against a mechanism which is locked in its singular position. When a small force is applied to move the four-bar mechanism away from its singularity, the force in the spring is released, providing a push-off force at the ankle joint. The main advantage of this type of locking is there is need for only a small unlocking force. The disadvantage is that when the singular position is not reached, the mechanism will not lock which can lead to malfunctioning of the device. Other examples can be found in [5], [6].

A friction force can be used to prevent an object from moving. Examples of this is the disk brake used in the automotive sector. A force is used to press an object against a rotating object. As the force grows, the friction between the two objects increases and the rotating movement is hindered. The advantage of this kind of lock is that it can be locked in any possible position and a relatively low friction force is enough to fix a non-moving joint. On the other hand, when the joint is moving the amount of friction force that has to be applied in order to stop the rotation will have to be a lot higher and this will cause energy losses. An example in the field of prosthetics is the Otto Bock 3R93 [1], in orthotics [7], [8]. A specific group of friction locks the overrunning clutches. These mechanisms use spring-loaded balls in between a shaft and a rotating cylinder. In one direction the balls will be pushed against the outer cylinder and the resulting high friction will obstruct the rotation. This can be combined with an active element that can disconnect the balls and allow free rotation in both directions. This principle is used in [9].

Finally, an other way of locking and unlocking joints is based on hydraulic damping. By opening and closing a valve in a hydraulic system, the damping in the system can be increased to a point where movement or rotation becomes impossible, and thus locking the joint. Reducing this damping will enable the joint to rotate. The Otto Bock 3R80 knee prosthesis [1] uses such a mechanism, where a stance phase valve is closed when an axial load is put on the knee joint (in this case the body weight). When the force is removed, at the end of the stance phase, the damping is reduced and the knee is able to flex. An other example of a hydraulic locking knee is the MAUCH hydraulic SNS knee [10]. As they are based on a different working principle, but with the same effect the magnetorheological (MR) brakes can also be put in this category. This type of brake/lock uses an MR fluid, which consists of magnetic particles mixed with any kind of liquid. This fluid is placed around a rotating part like a shaft causing a small damping. By changing the magnetic field around this fluid however, the particles in it are aligned which increases the damping. By controlling the magnetic field the damping of a joint can be controlled. This type of lock is also used in prosthetic knees [11] and a lot of other robotic devices [12], [13], [14]. The downside is that these systems are all dissipative and have associated energy losses.

All of the locking types above have advantages and disadvantages meaning the best suited device is highly application dependent. The need to develop the locking mechanism in our case follows from the study of the stiffness of the human knee joint [15]. During the initial stance phase a high stiffness is needed around the knee, during late stance the joint needs to be highly compliant so it can flex enough to provide ground clearance during the swing phase. This paper therefore presents an novel compact and light-weight design of a locking mechanism for the weight acceptance during the initial stance phase. The mechanism is part of the CYBERLEGs alpha-prosthesis [16].

The goal of the CYBERLEGs project is to develop a robotic system which can replace an amputated lower limb, both functionally and cognitively, while also assisting the contralateral leg and the hip. The target group consists of dysvascular transfemoral amputees and the system will allow them to walk, use stairs and go from sit-to-stand with limited energetic and cognitive effort [17].

In Section II the design of the locking mechanism is explained starting from the biomechanics of a human knee. Section III shows the test results of the locking mechanism used in an ankle-knee prosthesis with a passive knee joint. Concluding remarks can be found in Section IV.

II. Locking mechanism design

A. *Locking mechanism characteristics*

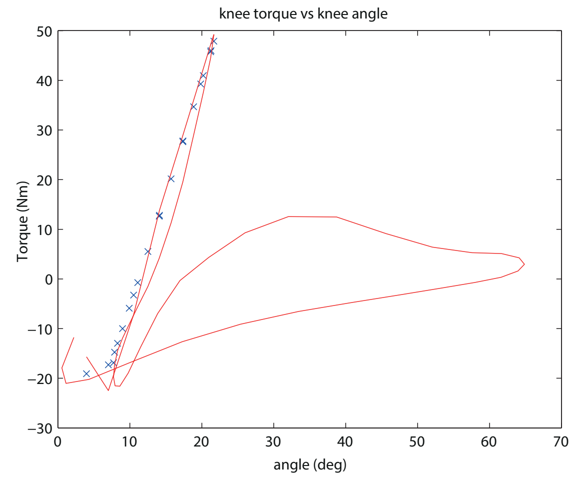

Fig. 1: Red line: torque-angle characteristic of a healthy knee joint for an 80 kg person during normal gait. Blue crosses: approximation of the weight acceptance phase using a linear torsional spring.

Using biomechanical data as a reference for knee behavior [15], the knee must provide a high stiffness during initial stance, and allow flexion during the swing phase. The high stiffness during early stance is well approximated by a linear torsional or linear compression or extension spring acted upon through a moment arm around the knee axis. Figure 1 shows the actual biomechanical data, shown in red, and the approximation of the stance stiffness is shown by the blue cross marks. Note that during the weight acceptance period the knee behavior is nearly linear in the torque/angle plane and loads and unloads at approximately the same point.

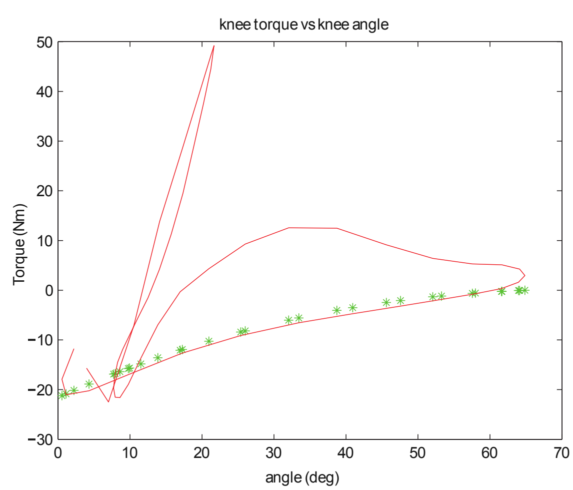

Fig. 2: Red line: torque-angle characteristic of a healthy knee joint for an 80 kg person during normal gait. Green stars: approximation of a spring providing the negative torques.

The requirements for the locking mechanism in normal operation can be deduced from this characteristic. The torque the mechanism should be able to withstand is about

$70Nm$ $(-20Nm\ to\ 50Nm)$ peak and when locked the mechanism should allow a certain compliance which allows a flexion of about $10°$. This leads to a joint stiffness of $7Nm/°$. When unlocked, the knee joint must be able to flex more than $60°$. First of all, to avoid having to lock the mechanism in two directions, a spring is placed in parallel to provide all the negative torques around the joint, a simulation of this spring can be found in Figure 2. In theory, the locking mechanism should only need to be lockable in one position, which is at a knee angle of about $7°$. However, since during some points of the gait cycle the amputee is entirely supported by the prosthesis, to prevent falls or reduce the risk of injuries the mechanism should be lockable at any position of the knee. The design goal was to make it capable of locking at every knee angle with an accuracy of $1°$.

The solution to this locking problem proposed by the authors is to combine a ratchet-and-pawl mechanism and a singularity locking. At heel strike, a buckling mechanism with a joint in the middle which is placed between the upper and the lower leg is close to its singular position. One of the two parts of the buckling mechanism is equipped with a compression spring. When the knee flexes, the mechanism buckles, without having any noticeable effect on the stiffness of the joint. A cable is connected to the center joint of the buckling mechanism and connected to a rotating axis which is also connected to a ratchet. When the ratchet is locked, the buckling mechanism can not move out of the way. If the knee joint would flex, the force on the buckling mechanism increases causing the spring to be compressed and exerting a torque around the knee joint. With an unlocked mechanism, the ratchet rotates freely and the spring buckles out of the way. The mechanism automatically returns to the singular position because of a return spring.

B. Comparison to other locking types

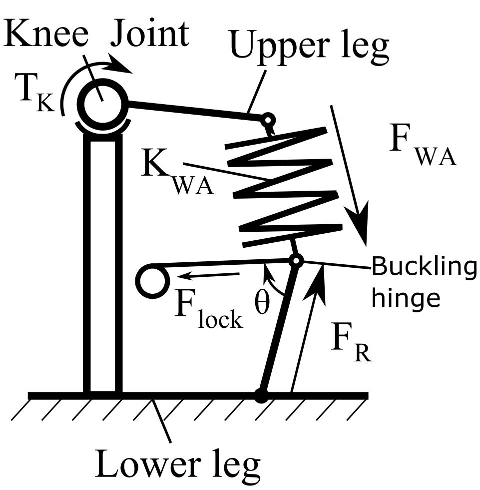

Fig. 3: First reduction in the locking force as a result of the buckling mechanism.

The advantage over the use of a simple ratchet and pawl and also over a friction lock is that this mechanism has a double reduction in locking force. The force going to the axis of the ratchet, F_{Lock}, is only a fraction of the force which is the result of the body weight acceptance F_{WA}. With notation as in Figure 3, we get:

$$F_{Lock} = F_{WA} \cos\theta \tag{1}$$

A second reduction in locking force is achieved thanks to the

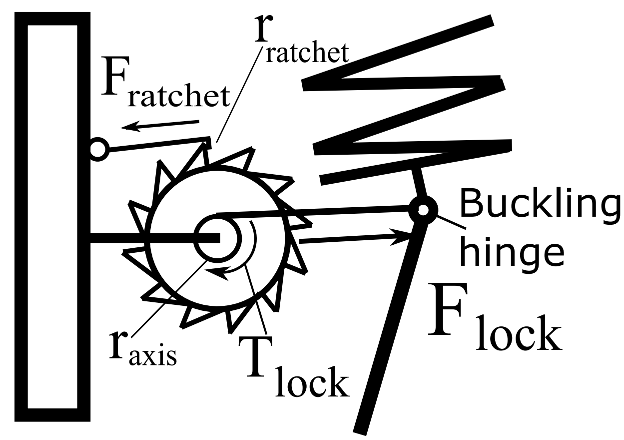

Fig. 4: Second reduction in the locking force as a result of ratchet design. For the definition of F_{lock} see Figure 3.

difference in diameter between the axis where the buckling cable is connected to and the ratchet. This also increases the accuracy of the ratchet. With notations as in Figure 4:

$$F_{Ratchet} = F_{Lock} \frac{r_{axis}}{r_{ratchet}} \tag{2}$$

Compared to a locking mechanism that uses purely a singular position to lock, the advantage of the singularity buckling locking is that it can be locked while the mechanism is not in the singular position. In comparison, if a four-bar mechanism were to be used and the extension of the knee joint at the end of the swing phase was not sufficient to reach the singularity, the mechanism would not be able to lock and the knee would collapse upon weight acceptance. In the case of the singularity buckling locking, the force in the locking cable would be higher than ideal but the mechanism would still be able to lock. If a buckling mechanism was used without the ratchet using only a servo motor, it would also be able to lock in any position, but there would be a high force on the motor which would require a high gear ratio and a robust (heavy) motor.

Finally, when comparing the mechanism to a hydraulic damper or MR brake, it is clear that a big advantage is that the energy that is stored in the system can be recovered as mechanical energy, bringing the leg back to almost-straight position after the weight acceptance phase rather than dissipating the energy by damping it.

The ratchet is built in such a way that the pawl is normally closed. A pawl-locking leaf spring was installed next to the pawl to assure this. The unlocking is done by means of a small bluebird AMS-A55H servo motor.

Using Equations 1 and 2 the force on the locking pawl can be calculated. Starting from a knee torque of 70 Nm over an

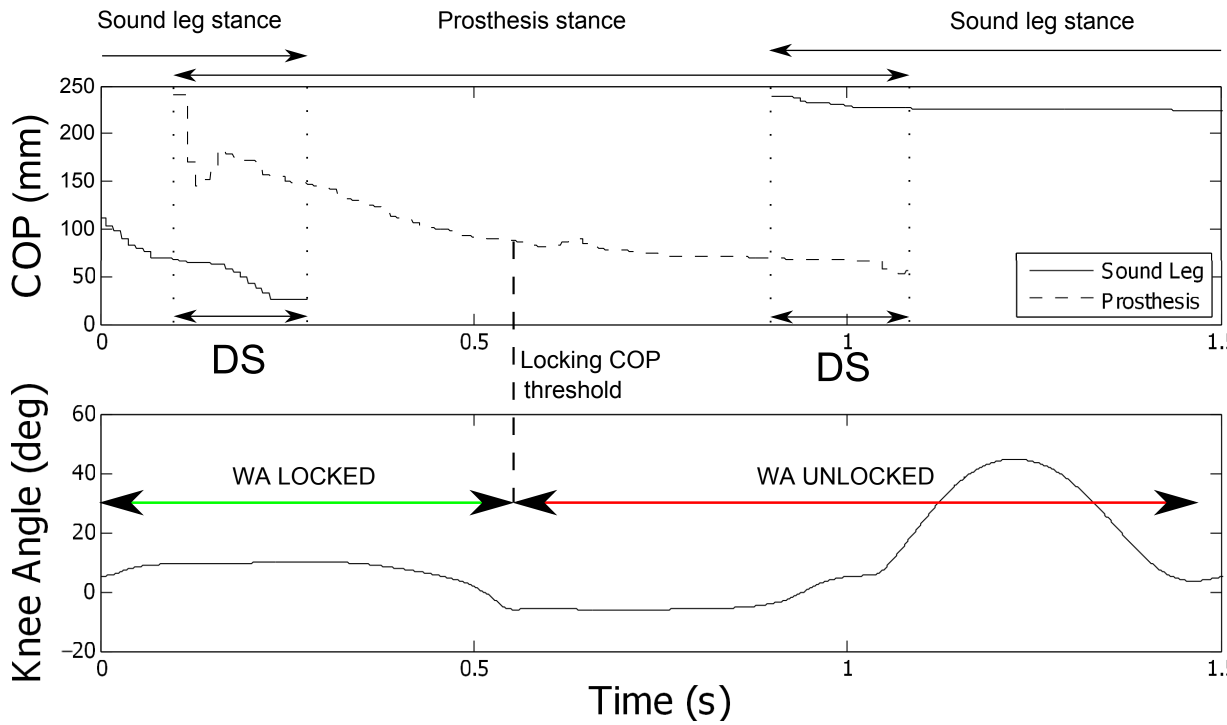

Fig. 5: Top: Measured center of pressure of the sound leg and the prosthesis during a test walk by an amputee. The graph shows where the sound leg and the prosthesis touch the ground and where there is double support (DS). Bottom: Measured knee angle during a test run, the state of the WA locking mechanism is shown as well as the COP threshold which is used to unlock it. It is clear that there is a phase with high stiffness (WA LOCKED) and one with high flexion (WA UNLOCKED).

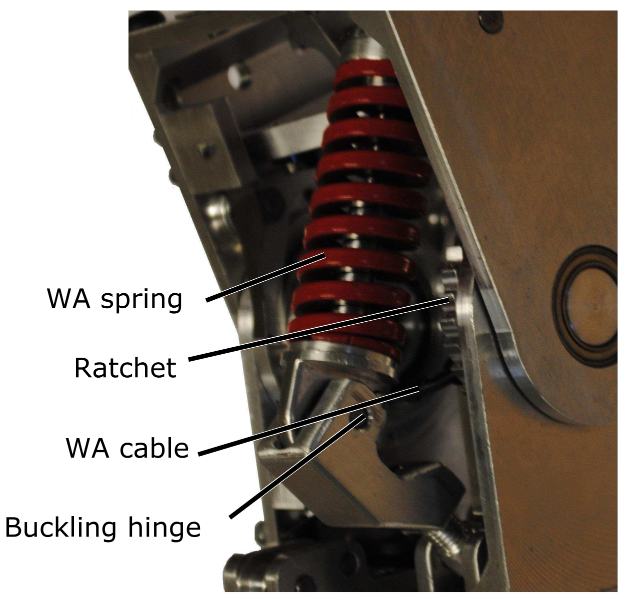

Fig. 6: Back of the locking mechanism. The red WA spring is mounted on the buckling structure and the hinge is connected to the ratchet axis by means of a cable.

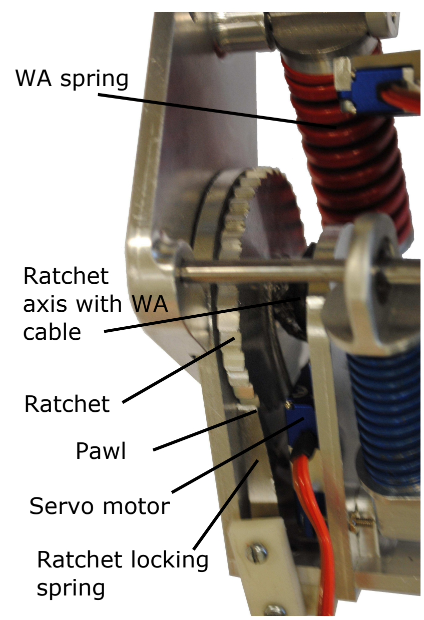

Fig. 7: Front of the locking mechanism. The pawl is pushed against the ratchet by the ratchet locking spring which locks the ratchet. The force in the WA cable is transferred to the ratchet axis and locked by the pawl.

moment arm of about 2 cm (this changes as the knee flexes), the radii of the ratchet and ratchet axis being 30mm and 7 mm respectively, and an estimated angle $\theta = 75°$ (see Figure 3), we get:

$$F_{Lock} = 3500N.\cos(75°) = 906N \tag{3}$$

$$F_{Ratchet} = 906N\frac{7mm}{30mm} = 211N \tag{4}$$

The ratchet sees about 6% of the force in the weight acceptance spring if it locks at the optimal position. In case of an unexpected stumble where the knee joint also has to be locked, the force can increase. For a theta angle of 60°,

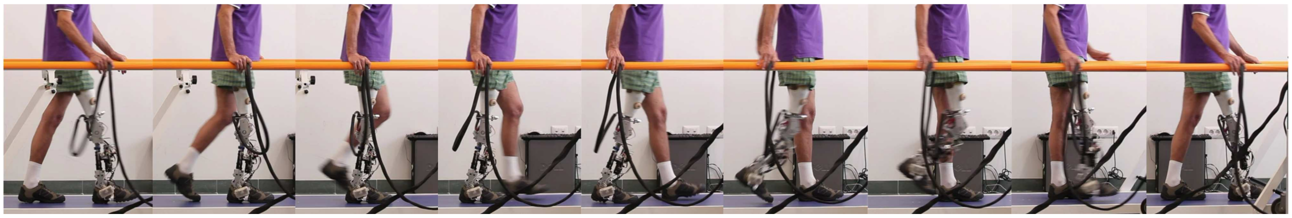

Fig. 8: Stills taken from a video of a test run with an amputee. One can see the knee is stiff during early stance and flexes during swing phase.

the force will double to just over 400N. Another advantage of the proposed locking mechanism over friction lockings and MR brakes is that no energy is required to keep the mechanism locked despite the force acting on it.

A change in knee angle of $1°$ corresponds to a change in distance between the ratchet axis and the buckling hinge of 1.2 mm. As the circumference of the ratchet axis is 44 mm, this is about 2.7% of a turn or about $10°$. The ratchet has 36 teeth or one every $10°$, so it is able to lock the knee with an accuracy of $1°$.

The physical realization of the locking mechanism can be seen in Figures 6, which shows the back of the knee joint, and 7, which shows the front. At the back of the joint the buckling mechanism can be seen sticking out, with the cable that links to buckling hinge to the ratchet axis. From the front view, you can see the ratchet and pawl, the bluebird motor responsible for the unlocking and the leaf spring that makes sure the neutral position of the pawl is locked (ratchet locking spring). The WA cable connecting the buckling hinge and the ratchet axis is wound around the axis.

III. Test results

The mechanism is integrated in the CYBERLEGs alpha-prosthesis knee joint. The control of this prosthesis is done through a state machine based on the joint encoder readings and pressure measurements of instrumented insoles [18]. The control of the locking mechanism can be done based on the readings of the insoles only. The moment a pressure is detected by the insole underneath the prosthetic leg, the mechanism is locked. When the center of pressure (COP) on the prosthetic foot hits a certain threshold this indicates that the weight acceptance phase is over. At this moment the force in the locking mechanism should be lower and it can be unlocked.

The measurements can be found in Figure 5. The top graph depicts the COP in the sound leg and the prosthesis. Every step the COP starts at the heel (COP=250mm) and as it moves to the toes the value decreases towards 0mm. Just before toe off the sound leg hits the ground and during the double support phase both insoles measure a value for the COP. From $t = 0$ to $t = 0.5s$ the weight acceptance phase occurs. The angle of the knee slightly increases while the weight acceptance mechanism is locked. When the COP crosses a threshold (which can be tuned for each individual), the mechanism unlocks and the knee angle increases to about 50 deg during the swing phase.

Figure 8 shows a part of the test run with one of the amputees. About 100 test runs have been performed by three amputees. They were short test runs on a catwalk, as it was the preference of the amputees not to do tests on a threadmill. Is it clear from the images that during the weight acceptance phase (frames 1-3), the knee joint is stiff and during the swing phase (frames 6-8) there is a high flexion providing the necessary ground clearance. The test runs were not long enough to measure any influence on their gait pattern, although it is expected that walking with weight acceptance during the early stance phase will increase the symmetry of the gait, as this is what happens in the contralateral leg too. This however is something that requires sufficient training with the prosthesis, as the behavior is different from that of the prostheses they are used to walking with.

IV. Conclusion

This paper described a novel locking mechanism used for the initial stance phase in a prosthetic knee joint. The proposed mechanism is capable of locking the high forces of weight acceptance in a human knee while still allowing a high flexion phase. Whereas a big part of the state-of-the-art in prosthetic knee joints either lock their knee during this phase or use a damper to dissipate the energy, the singularity buckling mechanism allows an elastic weight acceptance phase which causes less energy losses for the amputee. Thanks to the fact that the torque-angle characteristic is close to that of an average healthy human leg, the wearer will experience a higher walking comfort as with sufficient training the gait will be less asymmetric. The mechanism is more compact and lighter than a comparable ratchet mechanism and for this application more reliable than a singular position lock like a four-bar linkage. The cost of the system will be lower than any hydraulic or MR system as none of the components require high precision tooling. The mechanism has been tested by performing multiple test runs with three amputees over a catwalk. All amputees had sufficient support during stance phase and ground clearance during swing phase. In future tests, a load cell will be added to the weight acceptance spring to measure the exact amount of torque that is generated around the knee joint.

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