a.Walk: Exoskeleton Knee

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1 Abstract and Introduction

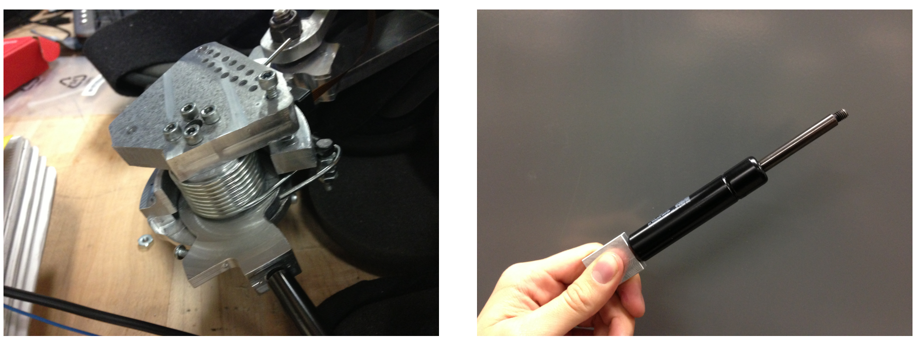
The objective of this project was to prototype a knee brace component of the human exo-skeleton used to assist paraplegic patients. This project is intended as an improvement to incorporate three recent design challenges:

1. Free extension at all times
2. Stop, damp, and free flexion with minimal interference
3. Operable with a simple actuation

The 3bar-4bar active hybrid linkage is an expansion from the recent direct attachment design of a locking and damping mechanism. The linkage configuration is actively configured based on the walking stage of the individual via a controllable, lockable pivot. A 3 bar configuration is engaged when the individual is in an upright position, allowing for a full extension. As he or she initiates their step, it switches to a 4 bar system that allows the stopping, damping, and free flexion of the knee. A linkage calculation was performed to optimize the bending angle and the physical feasibility of the linkage during walking. The designed link lengths were simulated in Working Model to verify the link system so that no physical interference would occur under given boundary conditions. Finally, a linear actuator was programmed and controlled using an Arduino control board to provide a simple actuation for the lockable pivot.

2 3 bar-4 bar Hybrid Linkage

A key design feature of this exoskeleton knee is the use of a hybrid 3-4 bar linkage. The feature is made possible by two mechanisms shown in Figure 1.



(a) Lockable Pivot

(b) Gas Spring

Figure 1

Here, Figure 1(a) shows the lockable pivot, while Figure 1(b) shows the gas spring, which provides damping.

The lockable pivot was an adaptation of the torsion lock via a torsion spring utilized in a recent design by Professor Kazerooni's lab group. Although the lockable pivot still used a torsion spring as its main component, it only provided the locking mechanism, unlike the torsion lock that provided both locking and damping. These were intentionally separated into two mechanisms for this project in order to achieve the hybrid linkage design. The linkage is a hybrid of a 3 bar and a 4 bar linkage because when the lockable pivot is locked, the 4 bar linkage loses a degree of freedom and becomes a 3 bar linkage. Since a 3 bar linkage is fixed, and a 4 bar linkage has a range of motion of one link relative to another, these two linkage types allowed both free and controlled movement of the knee. When the system is functioning as a 4 bar linkage, free movement is allowed, as seen in Figure 2.

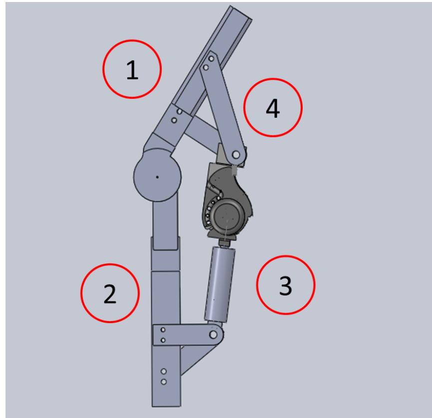
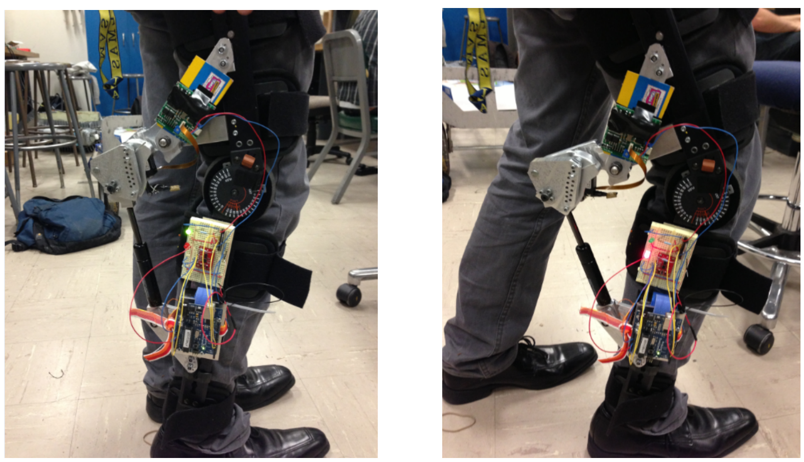


Figure 2: CAD model of mechanism with numbered links

The controlled movement is less intuitive, but still understandable. When the system's controllable pivot point is locked, and when the system functions as a 3 bar linkage, movement of the thigh relative to the shank is allowed by the compression or expansion of the 3rd link, which is composed primarily of a gas spring. This can be seen in Figure 3.



(a) Green LED indicates unlocked (b) Red LED indicates locked

Figure 3: Upright Position

3 Design Theory and Challenges

While the theory underlying the hybrid linkage is straightforward, the design issues are nuanced. For such a system to be worn, it is desirable to have a large range of motion available at the knee, so that the knee can be bent for the purpose of sitting. It is also desirable for the device to be as small as possible, so that it can be worn unobtrusively.

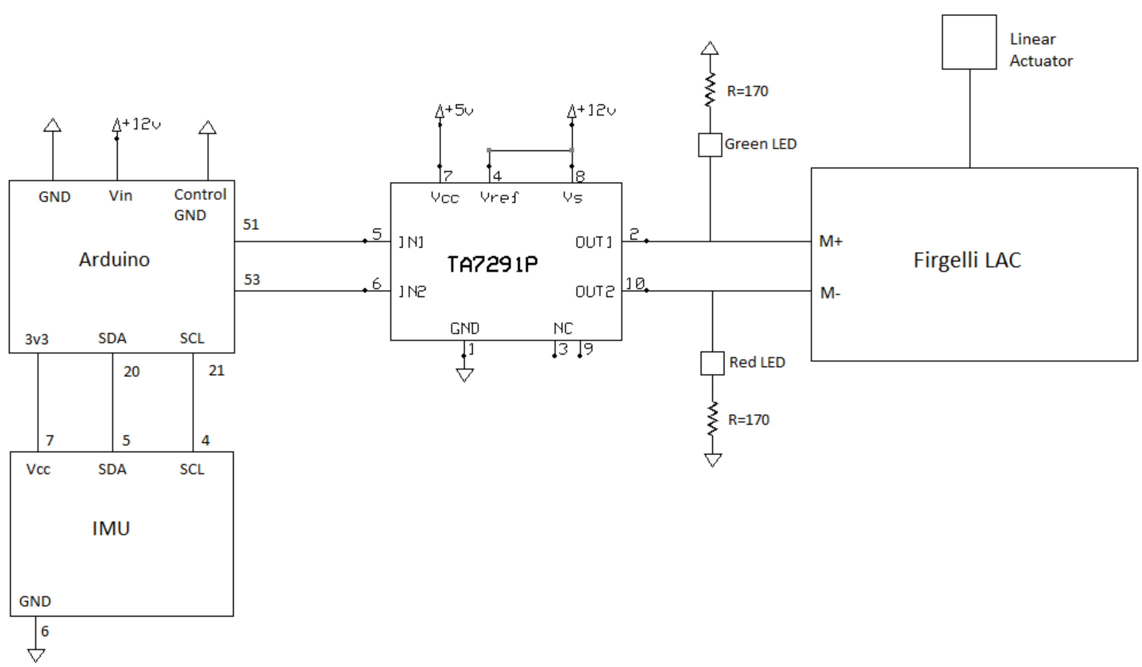
The analysis of 3 and 4 bar linkages found the critical factors constraining the size and range of motion of the device. The range of motion of the 3 bar linkage is constrained by the both the mounting points of the 3rd bar relative to the knee, by the relative amount the 3rd bar can change length, and by the amount of torque that is required at the knee. The amount that the 3rd bar can change in length is determined by both the amount the gas spring can compress relative to its length, and the length of the 4th linkage, which becomes part of the 3rd linkage when the system is in its 3 bar configuration. A gas spring is typically limited to compressing down to around 45% of its length, but once the length of the 4th linkage and the locking assembly is added to this, the 3rd bar can reduce its length by approximately 25%. This could still allow for a large range of motion if the pivot points were chosen so that on pivot point was very close to the knee relative to another. However, if such layout were chosen, a much larger force would have to be supplied by the 3rd bar than if the pivot points were evenly spaced from the knee in order to create a given moment at the knee. For example, this particular prototype was designed for a person's total weight of 130-140 lbs where each leg shared approximately half of the total weight using an optimized layout. In the above layout, however, a stronger gas spring would have been required. Therefore, compromises have to be made when picking gas springs and pivot points to achieve an acceptable range of motion and desirable size of the device.

A similar consideration must be made when choosing the length of the 4th bar. This bar's purpose is to allow motion of the thigh relative to the shank without having to compress the gas spring. To achieve a wider range of motion, the 4th bar must be made longer. However, this reduces the range of motion that can be controlled, and increases the size of the device. Therefore, a balance must be struck between the desired free-swing motion and the desired controlled motion.

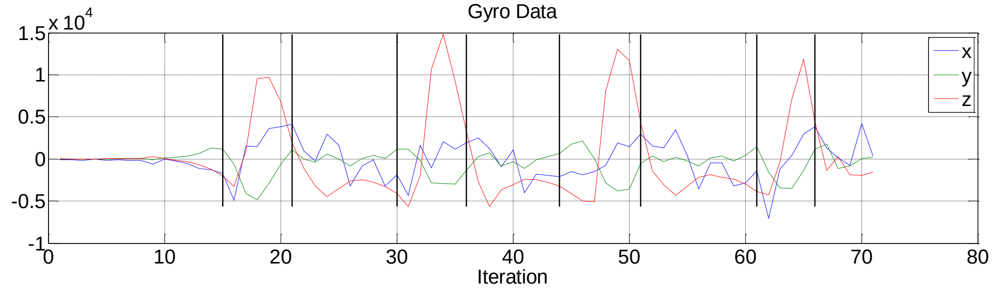
A final consideration to be made is whether to keep the 4 bar linkage in one plane, or whether to arrange links so that they are on different planes , which eliminates interference with one another. The benefit of using different planes is the larger range of motion that can be achieved as the links are not able to collide with one another. However, this will increases the width of the system and will introduce moments from out-of- plane forces. In the case of the brace, the overall size, while not unmanageable, could have been reduced if the lockable pivot was of a smaller diameter, and if the thigh (1st) and shank (2nd) links were stronger. These links and the knee joint were not designed as part of this project, but were instead the building blocks for the rest of the mechanism.

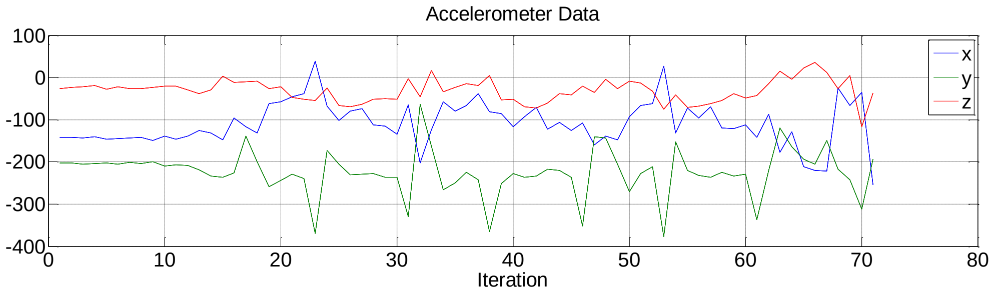
4 Programming Theory and Challenges

The knee is controlled by an Arduino Mega reading 3-axis acceleration and angular velocity data from the IMU3000. The Arduino then sends a control input to the H-bridge that switches voltage on the two motor inputs of the Firgelli Linear Actuator Control Board, or LAC. A schematic is shown below:



A typical walk cycle was analyzed to find critical points to lock and unlock the Firgelli linear actuator. The data for a typical 4-step walk cycle is shown below:





Take note that the Arduino requires slightly more than 40 milliseconds per iteration, but the exact time is not required for these calculations. The lock and unlock points are highlighted above on the Gyro data graph with vertical black lines. For locking, the procedure is roughly as follows: GyroZ must be positive, the derivative of GyroZ must be negative, and AccelY must have a slight negative slope. This indicates that the calf is rotating forwards, slowing down, and is beginning to accelerate upwards vertically slightly. The conditions are rewritten below for clarity:

```
If (Gz[19] > 0.1*pow(10,4) && (diffGz[18] < 0 || diffGz[17] < 0) && (diffAy[18:15] < -50)){
        output=0;
        //locked
}
```

In order to unlock, GyroZ must be less than a critical negative value, its derivative must be negative, and it can't have had a recent lock. This corresponds to the beginning of bending your knee while the rotation is still accelerating. The conditions are rewritten below for clarity, excluding the code that checks if the knee has recently locked:

```
If ((Gz[19] < -3000) && (diffGz[18] < -300)){
        output=1;
        //unlocked
}
```

This resulted in fairly smooth operation throughout a normal walking cycle. However, this does require a person to follow a somewhat specific pattern of steps, which might not necessarily be true for a paraplegic. The specific conditions would have to be modified somewhat for someone who had an extremely eccentric walk cycle.

There is another possible method of step detection that could be somewhat simple. A simple switch could be installed as a digital input pin to the Arduino, and while the switch is depressed, the user would perform their desired action. The Arduino could then save the last 1 second of data before the user released the switch. This data set could be used as a basis for a lock or unlock function, allowing the user to create custom triggers for the Arduino. If the user performed the same action with a low enough average least squares error, the Arduino would then trigger the actuator. This is highly similar in principle to how commercial products ranging from the Iphone to the Wii currently operate. However, it was beyond the scope of this project, where it was expected only to work for step detection for a healthy individual.

5 Conclusion

A 3bar-4bar active hybrid linkage design was utilized in this iteration of the exo-skeleton project in order to provide users with a refined motion from the direct attachment system. A separate lockable pivot and compressive gas spring replaced the integrated torsion lock that provided the locking and damping features single-handedly. Although the separation may make the entire system slightly bulkier than the previous version, it compensates by achieving the three design challenges, thereby effectively improving the user comfort level during their walking cycle. As aforementioned, balances must be found between the range of motion, the device size, and the structural integrity of the knee brace. These become more critical if extended applications were to be considered such as sitting down and standing up, which can be examined in the next iteration of this project.