Managing and Recycling Human Energy: A Mechanical Redesign of the UCSC Lower Limb Exoskeleton

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Overview

Lower limb exoskeletons are a staple in military research because they allow soldiers to carry heavy loads without enduring the weight. The existing lower limb exoskeletons are either gas or battery powered and therefore are not practical for extended periods of time. The LEX (UCSC's Lower Limb Exoskeleton) is designed to actuate based off of recycled pneumatic energy, which will allow for no time constraints. The human walking (gait) cycle consists of controlled falls which are essentially forward momentum. The knee acts as a damper and absorbs energy created from these falls to prevent it from fracturing bones [1]. The LEX utilizes this energy storage technique by compressing air cylinders at the knee and ankle joints upon flexion and storing the harvested energy in a reservoir tank. The pressurized air is then released into the hip and ankle joints to propel the exoskeleton forward. There are six cylinders total, one in each hip, knee, and ankle joint. Based off of force, angle, and pressure sensors, voltage controlled solenoid valves direct the flow of pressurized air at respective time intervals.

Mechanical Redesign of the Knee

The knee is now designed using a lever and fulcrum system which can fully compress a piston cylinder assembly based from a 20 degree knee bend (Fig. 1). This allows a maximum amount of energy to be harvested from the knee. There is a balance here between the displacement of the piston and the amount of force that is applied to the piston. Geometrically, the longer the lever is the greater the displacement, but physically, the longer the lever is the lesser the force becomes. A less bulky knee design allows for less added weight and gait cycle interruption, resulting in less energy required to actuate the LEX. A MATLAB program was written that, based on the height of the wearer, optimizes the knee design to minimize bulk and maximize force (Fig. 2).

*heavily annotated program can be found in Matlab/Simulink folder→ knee folder

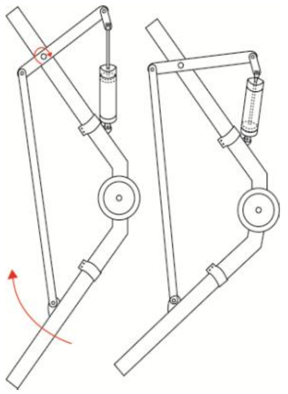


Figure 1. Mechanics of the knee

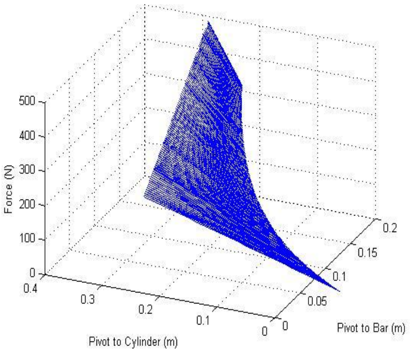


Figure 2. Balance of length vs. forces of lever

Recycling Energy

The knee and the ankle of the LEX feed compressed air into the reservoir tank; the air is then expelled into the hip and knee cylinders. The amount of work needed to walk was obtained from a motion capture study (Fig. 3-5) [2]. Each joint was analyzed to discover the amount of power it required to walk normally.

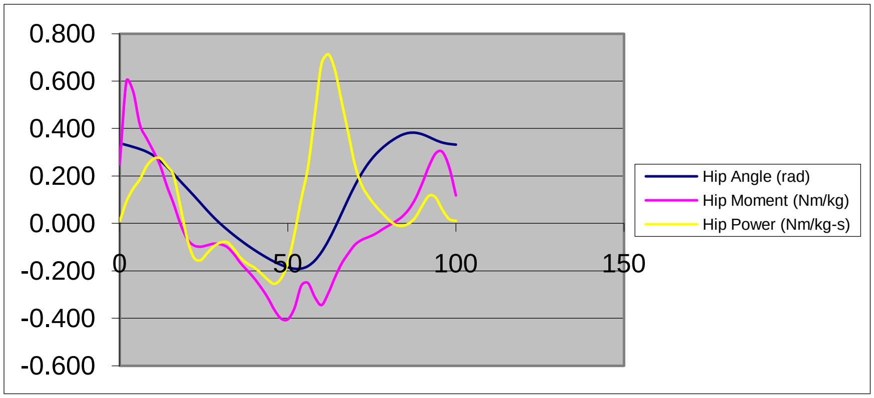


Figure 3.

Angle, moment, and power the hip endures while walking as % of the gait cycle.

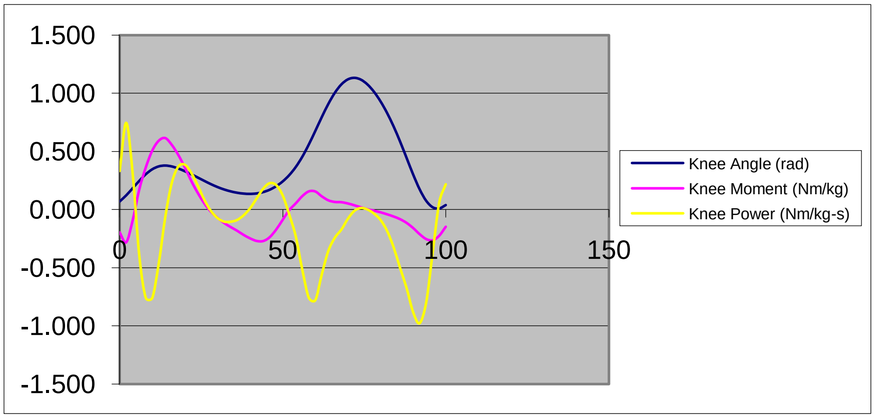


Figure 4.

Angle, moment, and power the knee endures while walking as % of the gait cycle.

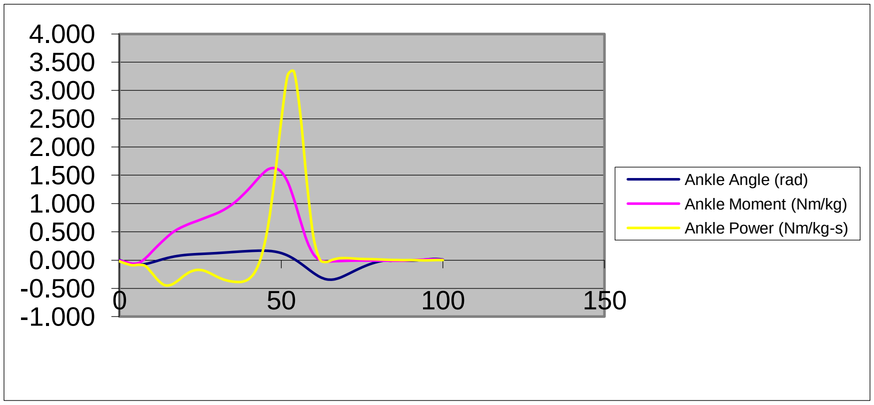


Figure 5.

Angle, moment, and power the ankle endures while walking as % of the gait cycle.

Depending on the weight of the person, the amount of work to walk varies (Fig. 6). For a heavier person, more energy is required to walk, but more force is applied to the piston face because of increased momentum and mass. However the amount of work obtained is not based on force but merely volume compression and the amount of harvested energy cannot increase without increasing the size of the cylinder.

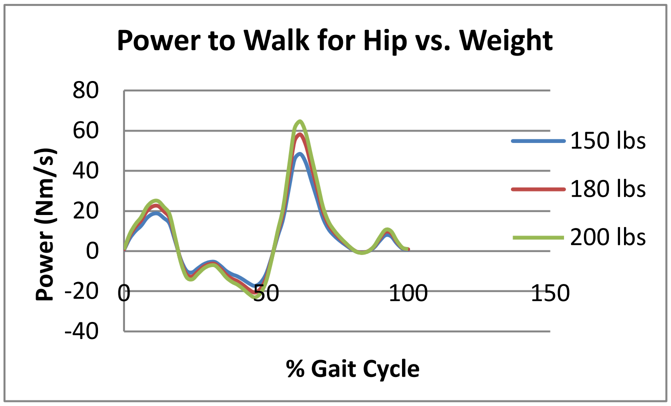


Figure 6. Power required from hip joint to walk based on weight of person. More power(+) required to propel forward with increasing weight.

To determine the percent of recyclable work the LEX could produce, approximations of a human weighing 150 pounds, walking at an average speed of 1.3 seconds/gait cycle were used. These parameters are easily variable as the power/kg is known and power is a function of time.

Power(weight)=(Power/kg)(kg)

Work(time)=(Power)(time)

The timing to harvest and expel energy is crucial because it must coincide with the gait cycle to control the amount of work the LEX can contribute to walking. The time to harvest energy from the knee is from 0-14% of the gait cycle, and 42-62% to harvest energy from the ankle [1]. The time to expel energy into the hip is 50-80%, and 44-62% to expel energy to the ankle. The more energy the LEX can harvest, the more work it can contribute. However, the longer the time period the pressure is released, the lower amount of work it can contribute. The amount of harvested energy was calculated with MATLAB using a quasi-static process where the pressure in the reservoir tank increased as the volume of the compressed cylinder decreased. The amount of contributed work is dependent on the time interval that the pressurized air is released at. An instantaneous pressure release would cause a jerky movement with maximum work whereas a longer time release allows for minimal work and smoother walking. For a quasi-static process the maximum amount of energy the 6” knee cylinder can produce is 0.5217 J. This small amount of energy is enough to provide a range of 7.15-41.38% work to the hip joint, or 2.49-11.57% work to the ankle joint dependent on time (Fig. 7). The ankle can produce .4321 J for a quasi-static process and therefore 5.92-34.28% work to the hip joint or 2.06-9.58% work to the ankle joint (Fig. 8). These numbers will decrease with increasing weight of the wearer because the work needed to walk will increase and the contributed work will remain constant because it is based on a change in volume.

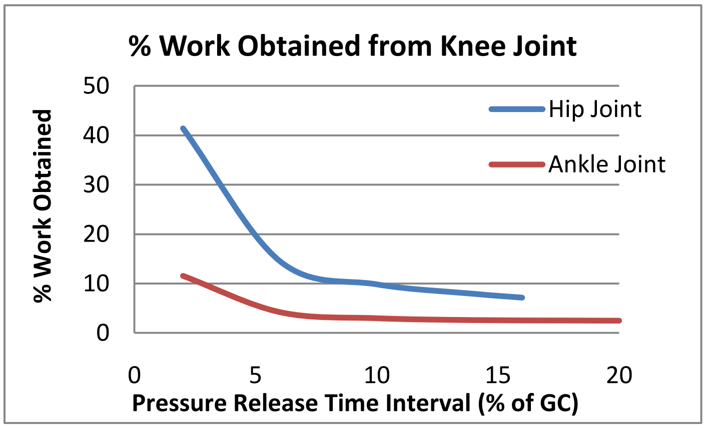


Figure 7.

% work obtained from only fully compressed knee cylinder. Total work is expelled in hip or ankle.

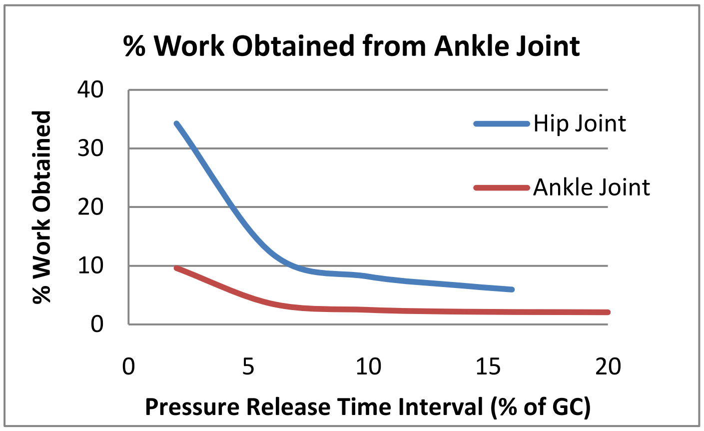


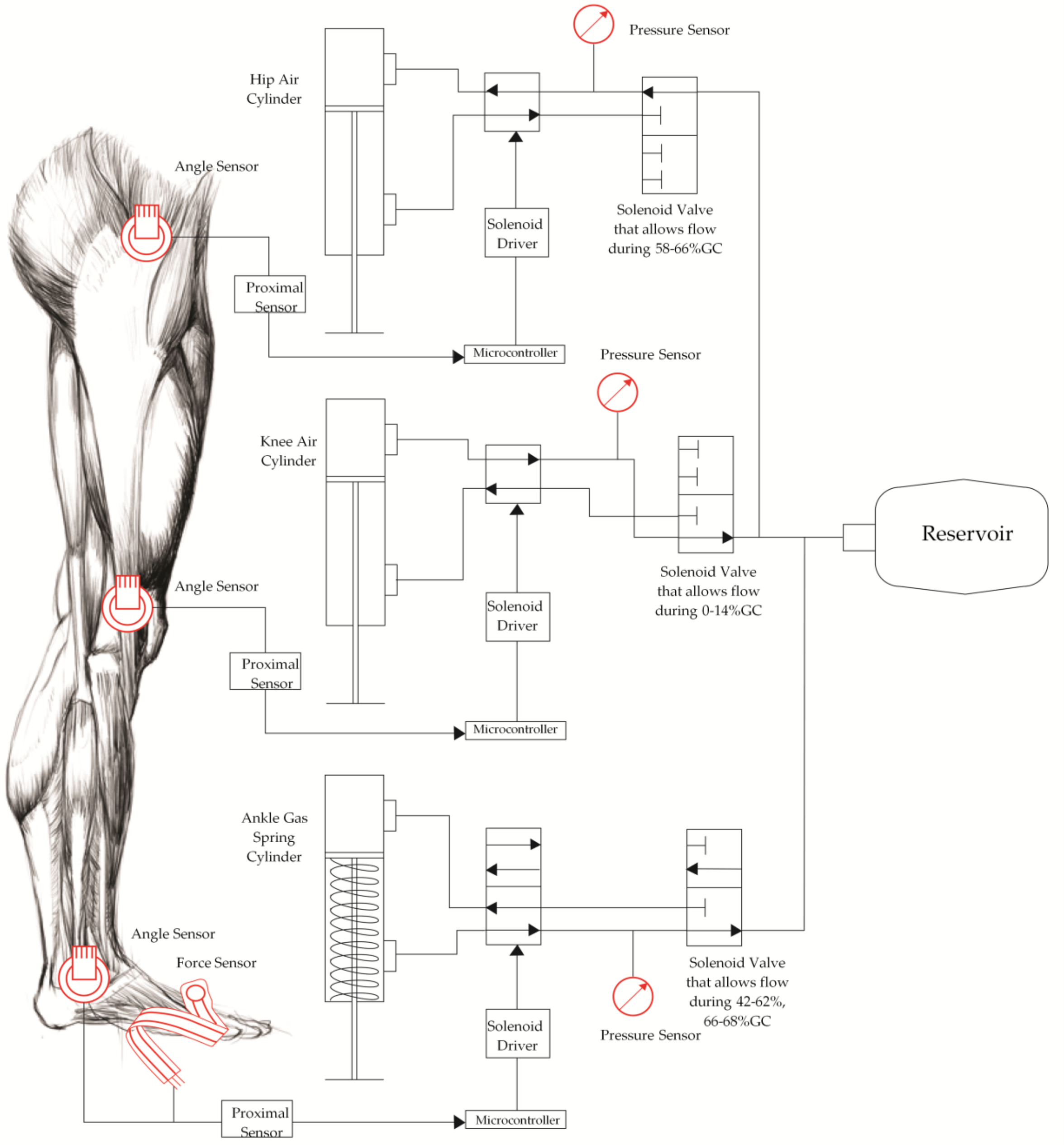
Figure 8.

% work obtained from only fully compressed ankle cylinder. Total work is expelled in hip or ankle.

Results

Approximately 10% of a 150 pound person walking at a speed of 1.3 seconds/gait cycle can be supported purely by recycled energy. This 10% is a median in order to achieve a uniform work contribution while maintaining a balance between fluidity and amount of work. In order to compensate for approximately 10% of the wearers load, the time that pressure is released to the hip is from 58-66% of the gait cycle, or .156 second period. The pressure released to the hip comes only from the energy stored by the knee joint. The pressure is released to the ankle from 66-68% of the gait cycle, or a .026 second period. The pressure released to the ankle comes only from the energy stored by the ankle. This will specifically account for 9.83% work at the hip joint and 9.58% work at the ankle joint. The fluidity of the hip is crucial in walking whereas fluidity to the ankle is not as important. Using this balance, approximately 10% of the energy needed to walk while supporting a heavy load will come from recycled energy with no pneumatic power supply. This will allow soldiers in the field, and eventually all backpackers, to support heavier loads with less muscle restriction and fatigue.

Pneumatic Schematic



Future Work

The work I have done this summer was based on a tank that initially starts at atmospheric temperature. Because the LEX is primarily concerned with renewable energy, only a portion of the work is being compensated for. Therefore it makes sense to not fill the reservoir tank with pressurized gas as it would mimic a battery and eventually deplete as well as create a higher cracking pressure to overcome. This can be further analyzed though and may have benefits. Also the math I worked with was quasi-static and is a maximum. In reality time is a large factor and this system needs to be analyzed dynamically. I researched how to do this and found several perspectives. I have listed them in the resources section so the next person to work on this can use them. The dynamics of it turned out to be rather complicated and someone with more experience in control systems seems necessary for this job. The system can be treated like a circuit where the reservoir tank is the capacitor and the tubing that transfers the air to the tank acts as a resistance. In the pneumatic schematic I used a gas spring cylinder instead of an air cylinder because the energy can be directly transferred through the spring because the ankle absorbs and expels energy. This can contribute to more work as well as increasing the volume of the cylinders that harvest energy. Please feel free to email me with questions at ralirieger@gmail.com.

References

[1]J. Perry, Gait Analysis: Normal and Pathological Function, New Jersey.

[2]J. Rose, J.G. Gamble, 1994, Human Walking, Second Edition, Williams & Wilkins, Baltimore. (Power graphs)

Future Work References

K. Ogata, “Mathematical Modeling of Fluid Systems and Thermal Systems,” in Modern Control Engineering, fourth ed. New Jersey.

**Look in the Bionics Lab’s external hard drive under Rachel Rieger→ sources to find more, specifically one from UCB