Implementation of Pneumatic Air Muscle for Actuating Knee Exoskeleton Using Four-Bar Linkage

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Abstract: The knee exoskeleton is a device that assists users with weak knees to walk. It consists of a mechanical construction put around the human knee which is equipped with an actuator for movement. One mechanism that can be used to mimic movement of the real knee is the four-bar linkage. This research explores the possibility of using pneumatic air muscles as actuators for a knee exoskeleton with four-bar linkage implementation. A pneumatic air muscle is a single-acting linear actuator that contracts when filled with pressurized air, mimicking muscle contraction. It is much lighter than electrical motors, but—according to characterization done in this research—is difficult to control due to its inconsistent torque output. Nevertheless, this research shows that simple gait movements can be simulated using a knee exoskeleton actuated by pneumatic air muscles with an on-off control scheme.

Keywords: Pneumatic air muscle, knee exoskeleton, four-bar linkage, gait cycle

1. Introduction

Modern developments in technology have allowed artificial devices known as orthoses to aid human limb movement and support. One common orthosis is a leg exoskeleton that improves the strength of the knee joint and guides its movement in a fixed direction for users who do not attain proper use of their knee. Motorized exoskeletons, however, tend to be heavy and inconvenient due to inclusion of an actuator and means of power transmission.

This research aims to create an active knee exoskeleton with automatic actuation that is lightweight and cost-effective. The pneumatic air muscle (PAM) and the four-bar linkage mechanism (4BL) are to be used in the prototype.

2. Literature Survey

2.1. *Human Gait Cycle*

To provide an accurate walking simulation for the user, the knee movement of the exoskeleton needs to match the natural progression of the human knee during a typical gait cycle. The three joints of the leg conform to a particular pattern during walking. The purpose of the exoskeleton is to use the current angle of the hip as reference to position the knee at a certain angle. As the hip changes angle throughout the user's gait, the knee follows along creating a certain pattern of progression

2.2. *Preceding Research Projects*

In 2016, Adamlu *et al.* (2016) designed a knee exoskeleton of a fixed size using a leg brace as the supporting structure and an electric DC motor paired with a gear-train as the primary actuator. This design, however, was slow and heavy, with an operating gait speed of 2 Hz and a weight of 4.7 kg.

In 2017, Santo *et al.* (2017) redesigned the exoskeleton to feature a frame made primarily of light 3D-printable material as well as early implementation of the PAM and 4BL. The design, however, was yet to be wearable and lacks an input-to-output mathematical model of the actuation.

2.3. *Pneumatic Air Muscle*

The PAM is a single-acting cylinder with the following advantages: light weight, customizability, safe operation, easy replaceability, and low cost. However, the PAM is difficult to precisely control and its actuation force decreases over its contraction. The PAM is to be created from a rubber tube clamped on both ends and given a fitting on one end. This McKibben-inspired design is to be the primary actuator of the exoskeleton to reduce the weight and cost.

3. Methodology

3.1. Material and Component Selection

The exoskeleton is to read the following inputs: hip angle, knee angle, and foot position. These points are read by an inertial measurement unit (IMU), a potentiometer paired with a 15:1 gear-train, and a limit switch in the bottom of the fleet, respectively. With these three data, the system is able to determine at which point of the gait cycle the user is currently in. These data are recorded and processed by an Arduino microcontroller. The Arduino houses the program written in C++ language, and also acts as the power source for all three sensors (each using 5V). The knee angle is actuated using the PAM, which is controlled by a solenoid valve. An optocoupler relay is used to step-up the voltage output of the Arduino to accommodate for the valve's voltage requirement of 24V.

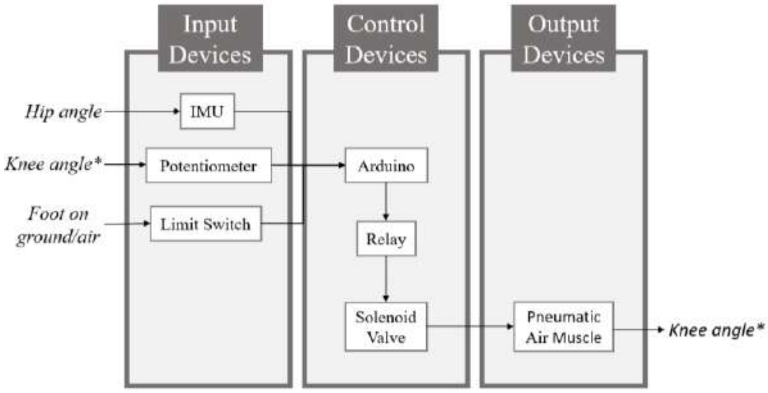

Figure 1: Components used in prototype

All control devices and other complementary components are housed in an acrylic box separately from the exoskeleton. This is a safer alternative and allows the user to move freely without carrying the electrical system on their leg.

3.2. Load Analysis

The actuator is required to be able to withstand the load during the entire gait cycle. The knee experiences two kinds of loads, one for each half of the gait cycle: the swing phase and stance phase. The swing phase occurs when the foot is in the air, and the stance phase on the ground.

During swing phase, the load on the knee comes from the weight of the bottom half of the leg. The instantaneous load can be calculated using the following formula:

$$T_w = 0.1302h_b \cdot 0.059m_b \cdot g \cdot \sin(\phi - \phi_c - \beta) \tag{1}$$

Where T_w is the torque on the knee, h_b is the user's height, m_b is the user's mass, ϕ-ϕ_c is the knee angle, and β is the hip angle. Using the average measurements for the typical human leg, the user's mass and height can used to find the center of mass of the bottom half of the leg as well as its distance from the knee. The user is assumed to be 170 cm in height and 70 kg in mass. The swing load is a second-order function with a maximum value of 6.45 Nm at a hip angle of -3.5°.

During stance phase, the load on the knee comes from the weight of rest of the body. Whereas the swing load changes with knee angle, the stance load only applies to a knee angle of 0° and can be found using the following formula:

$$T_{stand} = [W_s(r_s - r_{cs}) + (W_b + W_l)r_s] sin\ 10° \tag{2}$$

Where W_s, W_b, and W_l are weights of the shank, body, and thigh, respectively, r_s is the length of the shank and r_{cs} is the length between the knee and the shank's center of mass. The human body is assumed to have a shank angle of 10° when standing. Assuming the user is 170 cm in height and 70 kg in mass, the standing load is 37.053 Nm, or 18.527 Nm/leg.

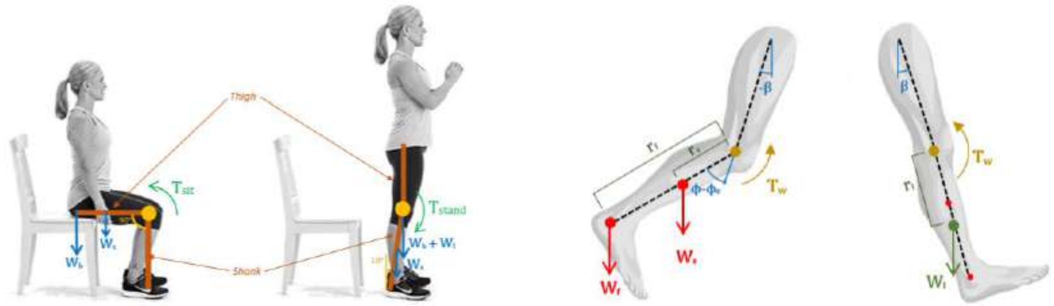

Figure 2: Torsion on the knee and relevant variables during the stance and swing phases

3.3. Pneumatic Air Muscle Experimentation

The PAM design follows that of Jeremy Santo's. It is designed to be as light as possible and minimize cost. Required materials include a 6x10 latex tube, two 5/8" hose clamps, 18 mm nylon cable sleeves, a 5 mm pneumatic hex fitting, and a hose nipple.

A testing rig was also created to gauge the pulling force of the PAM for each contraction length. This rig consists of an aluminum profile frame and a luggage scale fixed into place. One end of the PAM is tied to the aluminum frame, and the other to the scale. Note that PAMs only provide pulling force. A PAM of length 25.8 cm is tested for pressures of 2, 2.5, 3, 3.5, 4, and 5 bars.

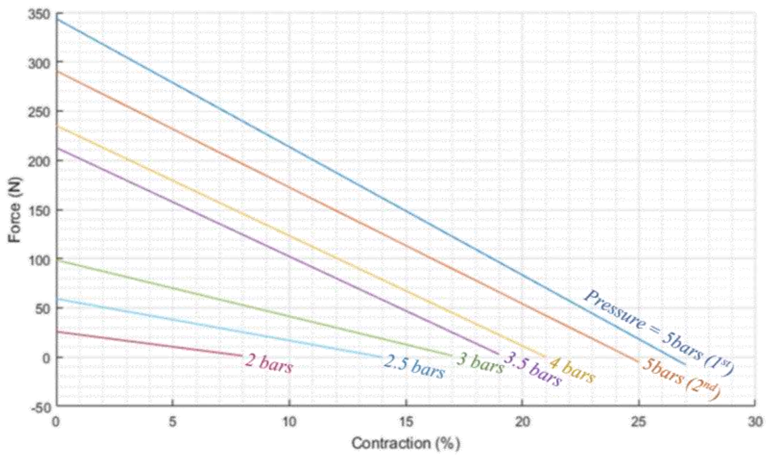

Figure 3: Contraction vs force graphs for all tested pressures

Results are shown in Figure 3 for all pressures. The graph shows that the PAM's output force decreases with contraction, and higher pressures allow for higher overall forces and ultimate contraction length. Although the PAM was designed to prevent bloating, creasing, and exploding at higher pressures, lower pressures are preferred as it reduces risk of danger and encourages use of smaller compressors for portability. Lower pressures, however, result in lower forces against load. An operating pressure of four bars is ultimately used for the exoskeleton.

4. Results and Discussion

4.1. Gait Testing

The exoskeleton is to have an on-off control system due to difficulty implementing PID onto the PAM. This means that the knee is either flexed or extended with no stopping room in-between. To determine where in the gait cycle the knee needs to be flexed or extended, the cycle is divided into four stages in sequence which transition when a certain condition is fulfilled: terminal stance, swing, terminal swing, and stance. The extending PAM is activated during the swing and terminal swing phases, and the flexing PAM is activated during the stance and terminal stance phases.

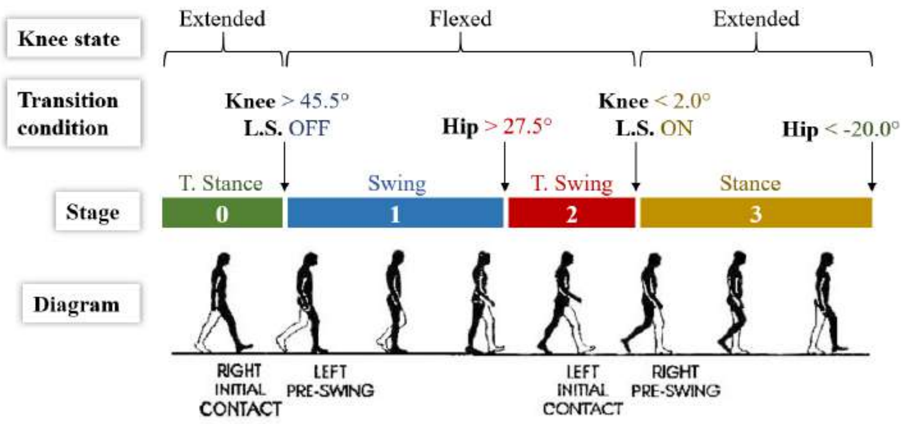

Figure 4: Gait cycle divided into four segments based on PAM actuation

The exoskeleton is designed to have a knee flexure of 28.7°, which is the minimum allowable angle for the leg to be able to pass through the swing phase. For gait testing, the exoskeleton is held by hand to progress through the four stages. The knee is able to flex up to 27.04°. This reduction is possibly caused by paddings added in the 4BL to absorb impact.

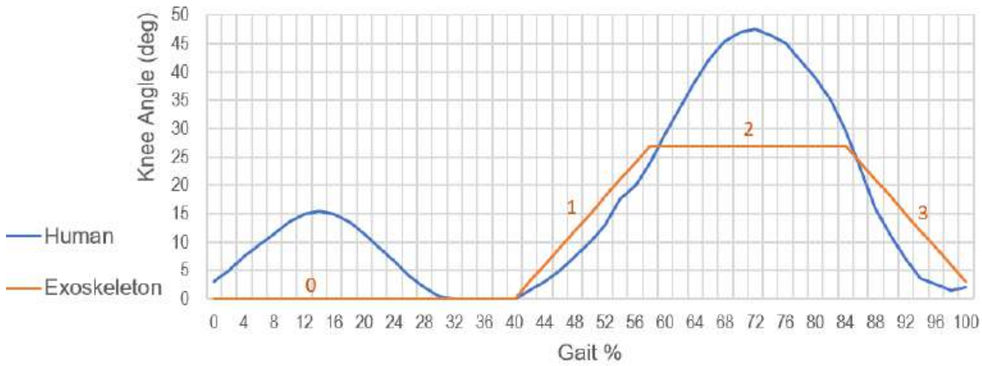

Figure 5: Exoskeleton knee progression vs natural knee progression

The exoskeleton cannot replicate the smooth movement of the human knee. However, it can roughly allow gait via the four stages mentioned earlier. Actuation speeds vary with an average of roughly 0.2 seconds, which is enough for the average walking speed of 1 Hz.

4.2. Load Testing

To test the torque of the exoskeleton, its thigh segment is held in place and a variable weight (rice bucket) is hung at a certain distance from the knee. The torque conforms to a certain pattern due to the knee angle, and to find this function, the knee angle is recorded as the weight is varied. Accounting for the gravity constant and distance of the weight to the knee, the extending torque can be derived from the following formula:

$$T_w = 0.2213\ (W + 25.5)\cos(\beta + 10°) \tag{3}$$

Where T_w is the load torque, W is the weight of the rice bucket, and $\beta+10°$ is the angle of the knee. This creates the following graphs, comparing the experimental torques to the designed torques.

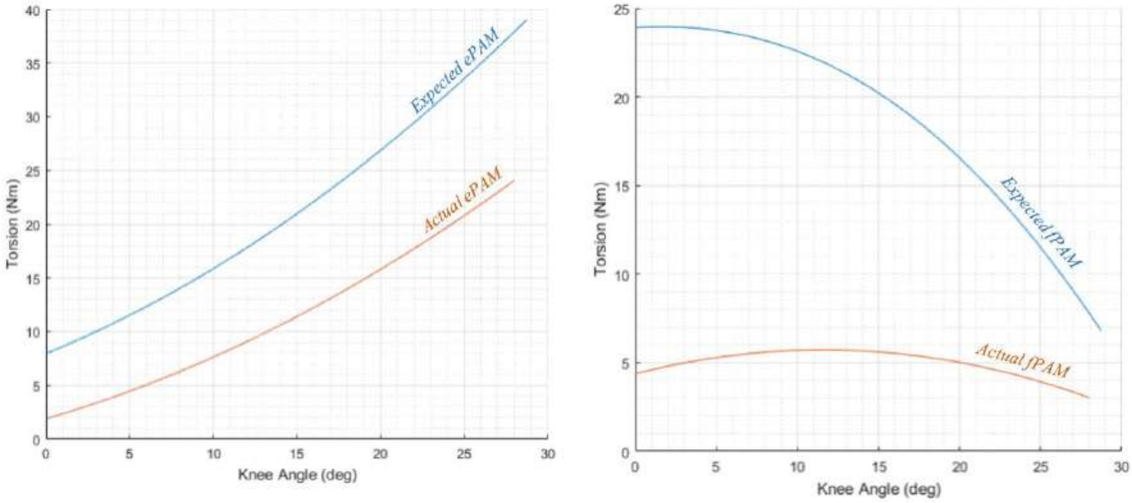

Figure 6: Extending (left) and flexing (right) PAM torques (experimental versus design)

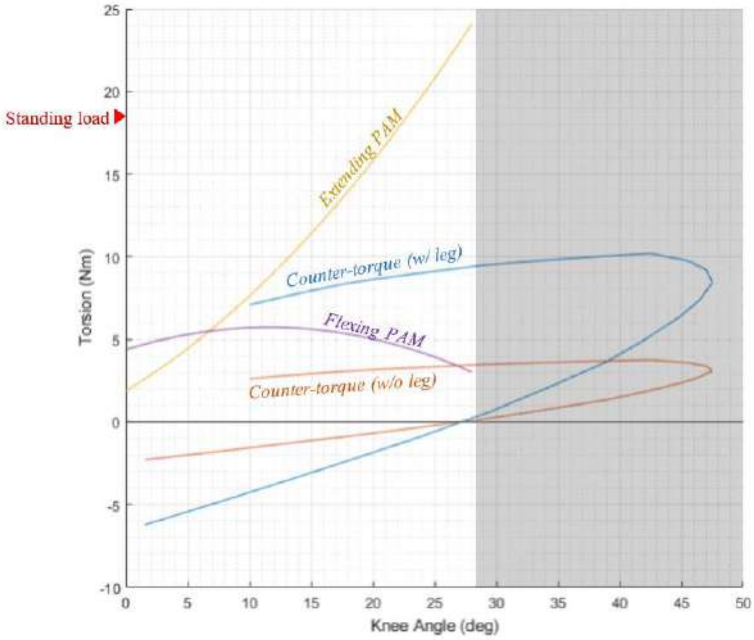

Figure 7: PAM and load torsions (actual)

The actual extending PAM performance has a reduction beginning from 6 Nm to 15 Nm towards the end of the operating range of the exoskeleton. As with the extending PAM, the actual performance is significantly weaker with a torque reduction beginning from 19.5 Nm to 4 Nm towards the end of the operating range. In addition, the peak is shifted from 1.5° to 12° knee angle.

The extending PAM torsion at zero knee angle is 1.9 Nm, which supports only 10.3% of the standing load (from 18.5 Nm). The flexing PAM torsion at maximum flexure is 2.7 Nm, which supports only 28.4% of the highest counter-torque load (from 9.5 Nm). This percentage increases towards lower knee angles as the force of the flexing PAM becomes stronger and the counter-torque becomes weaker.

The flexing PAM is, however, able to withstand the counter torque without the user's leg up to about 27°.

This significant difference between designed torque and actual torque may be caused a number of things. One, an incorrect assumption that the PAM attains its contraction-to-force ratio regardless of its length as long as the hose's diameter, hose's thickness, sleeve's diameter, and materials used remain the same. This may not be the case as the sleeve as an absolute limit in diameter. Another possible reason is errors in mathematical modelling due to several approximations as well as unreliable experimental data due to inconducive experiment environments or inaccurate data-taking.

5. Conclusion

In conclusion, the proposed design is, in actuality, only able to withstand a small percentage of the standing and swing loads. The code and on-off control system work as intended and can roughly simulate human gait when worn. The resulting exoskeleton is wearable on one leg, however, wearing two concurrently may not be possible as it remains too thick to fit in-between the legs. It has smooth movement from the 4BL formation, a weight of 4.2 kg, an operating range of about 27°, and a minimum operational pressure of four bars.

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