

# POWER COST OF AN ELECTRONIC CONTROL SYSTEM FOR A STANCE CONTROL KNEE-ANKLE-FOOT ORTHOSIS

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## INTRODUCTION

Patients with weak quadriceps are commonly prescribed a knee-ankle-foot orthosis (KAFO). These devices allow patients to load weight onto their braced leg by keeping the knee locked in full extension. Although this type of KAFO allows the patient to walk, the extended leg causes abnormal gait, decreasing gait efficiency, and resulting in higher energy expenditure [1].

In recent years, a new type of KAFO has been designed to provide knee support in stance while allowing free knee motion during swing. This feature provides advantages over previous designs; such as, faster walking speeds, increased mobility, reduced energy expenditure, and more symmetrical gait patterns. These new functional KAFOs are known as Stance-Control Knee-Ankle-Foot Orthoses (SCKAFO) [1].

While various SCKAFO designs have emerged, many practical limitations have hindered the ability to produce a low-cost, commercially viable solution. Some of the most common limitations are size, weight, cost, and functionality [1].

Current SCKAFO designs are either mechanical or electro-mechanical. For the electro-mechanical approach, electronic systems are used to control when a SCKAFO resists knee flexion or disengages for free knee motion. Examples of this technology include the "E-knee", the "Dynamic Knee Brace System" and the "Ottawalk".

The E-knee, by Becker Orthopedic, uses multiple sensors on a footplate and a clutch lock which locks in any position when triggered. A microprocessor is programmed to lock and unlock the knee at the proper time. [2]

The Dynamic Knee Brace System (DKBS) uses a wrap-spring clutch, footswitches, a linear solenoid, a battery pack, and control circuitry. Power for the entire system is supplied by six 9 V batteries. The control system and battery pack weighed 0.57 kg and are carried in a waist pack. [3]

The "Ottawalk", by Yakimovich et al., uses a friction based mechanism which enables the knee to lock in any position. The original electro-mechanical design included force sensing resistors (FSRs), a control system and a solenoid. [1]

In each of these systems, power requirements influence the size and weight of the battery module. A small, lightweight, embedded electronic control system with low power consumption would benefit consumers by providing a functional and more cosmetically appealing option for SCKAFO control.

## OBJECTIVE

The objective of this project was to design an embedded electronic control system for electro-mechanical SCKAFO systems. Building on the electro-mechanical "Ottawalk" design, the electronic control system provides seamless switching between stance mode and free motion of the knee.

The electronic control system must operate for at least 12 hours without recharging the battery module, since the SCKAFO will be used daily by the consumer. To increase usability the design must be small, quiet, light weight and inexpensive.

## DESIGN

The control system uses 1.5" square force sensing resistors (FSRs) located on the plantar surface of the AFO portion to determine the phase of gait. Pressure signals from these FSRs (model 406, Interlink Electronics) are converted to voltages and processed by an on-board PIC microcontroller (PIC18F8722, Microchip). This microcontroller controls an actuator that engages or disengages the stance control mechanism.

The user can select between three modes of operation (free knee motion, locked knee in extension, and stance control) by using a toggle switch.

A calibration button and indicator are incorporated into the hardware module to adjust for variable plantar pressures or temperature due to footwear that affect FSR output (i.e., lacing shoes tightly, etc.).

Appropriate timing for joint deactivation is essential to achieve smooth gait. The joint will ideally deactivate before toe-off when walking. Joint activation must occur during any limb loading activity, including stairs, ramps, and variable locomotor activities.

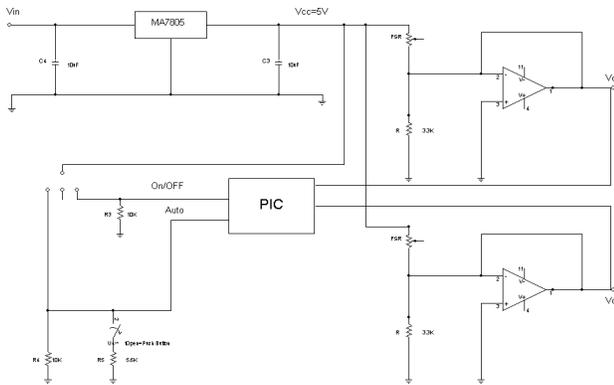


Figure 1: Schematic of electronic control system

The complete schematic of the circuit design is shown in Figure 1. The electronic control system is composed of four main sections: voltage regulator, sensing circuit, processing circuit and actuating circuit.

Voltage Regulator

The PIC microcontroller requires an operating voltage between 2.0V - 5.5 volts [4] and the rated value for the servo motor is 4.8V [5]. A 7805 voltage regulator (LM7805 with TO-220 packaging, National Semiconductor) is used to drop the voltage from a 9V battery source and keep the voltage at a constant 5V.

Sensing Circuit

FSRs use the electrical property of resistance to measure the pressure applied to a given surface. When pressure is applied to the sensor, a stronger connection is made between the contact layers, hence the conductivity of the sensor increases leading to an overall resistance decrease.

The output signal was obtained by creating a voltage divider between the FSR and a 3.3kΩ resistor. As pressure on the FSR increases its resistance decreases, causing the output voltage to increase proportionally. This configuration results in an approximately linear relation between pressure and

output voltage, allowing the FSRs to respond to varying levels of pressure.

Processing circuit

The microcontroller checks the current position (On, Off, or Auto) of the toggle switch. For On and Off mode, the program enables or disables the output to the actuator respectively. When the output is disabled, or in the case of power failure, the default position is with the knee locked in extension (Off). When the toggle switch is set to Auto mode, two functions are called. The first is the calibration function which can recalibrate the system. The second function called SCKAFO() provides stance control.

Different programs are required, depending on the choice of actuator. In the case of a solenoid, a 5V digital output is required for activation and a 0V digital output would turn the actuator off. In the case of a servo motor, a digital output using Pulse Width Modulation (PWM) is required to provide two positions (swing and stance). The SCKAFO function sets a duty cycle of 5.4% (based on a period of 20 ms) for stance mode and 8.1% for swing mode. The design structure of the SCKAFO() function was implemented using C language, compiled using MPLAB IDE and then programmed onto the PIC.

Actuating Circuit

An actuating circuit interfaces the digital output from the PIC with our actuator. In the case of the servo motor, the on-board Vcc and GND terminals from the PIC development board are used to supply power and a digital output is used to provide the control signal.

In the case of the solenoid a MOSFET based circuit (shown in Figure 2) was used. The digital output from the PIC was sent to the gate of the MOSFET, the source was connected to Vcc and the drain was connected to the solenoid.

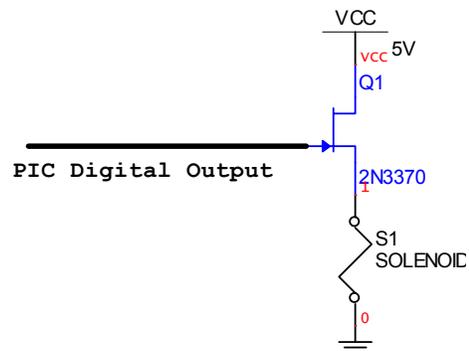


Figure 2: Solenoid actuating circuit

## METHODS

A comparative power analysis was performed using two actuators; a solenoid (Ledex Tubular Solenoid Part# 195205-227) and a digital servo motor (Futaba S3150). Two power supplies were used, a 9V battery to power the sensing circuit and a variable DC power supply for the actuating circuit. The solenoid DC power supply was set to 9V and the servo power supply was set to 5V. The same sensing circuit was used for both actuators.

A PIC digital output using PWM provided the control signal to the servo motor. In the case of the solenoid, a single digital output was connected to the input of a FET-based circuit.

Current measurements were taken for the sensing and actuating circuits. Peak current measurements were obtained by selecting the highest reading over four trials. Average current values were obtained by averaging four readings. All measurements were performed with no mechanical load applied to the actuators.

To obtain power values, the supplied voltage was multiplied by the measured currents. This provided power consumption values for the different states of the circuit.

The total power dissipated by the solenoid-based circuit ( $P_1$ ) was obtained by adding the power consumed by the sensing circuit ( $P_{sON}$  /  $P_{sOFF}$ ) plus the power consumed by the actuating circuit ( $P_{aON}$  /  $P_{aOFF}$ ). A 40% duty cycle (swing mode) was assumed to calculate the time spent in each state. Formula (1) shows the calculation of total power consumption by the solenoid-based circuit.

$$P_1 = 0.4(P_{sON} + P_{aON}) + 0.6(P_{sOFF} + P_{aON}) \quad (1)$$

The total power dissipated by the servo motor-based circuit ( $P_2$ ) was obtained by adding the power consumed by the sensing circuit ( $P_{sON}$  /  $P_{sOFF}$ ) plus the power consumed by the actuating circuit ( $P_{aON}$  /  $P_{aOFF}$  /  $P_{aT}$ ). The last term in the calculation shown in Formula (2) is needed to account for the spike in current that occurs during the transition between the two states of the servo motor (swing to stance, stance to swing).

$$P_2 = 0.4(P_{sON} + P_{aON}) + 0.6(P_{sOFF} + P_{aON}) + 0.01P_{aT} \quad (2)$$

Using the resulting power consumption values a projection was made for total run-time, assuming a 9V 2200 mAh battery.

## RESULTS

Table 1 displays power consumption values obtained for the sensing circuit and the two choices of actuating circuits in the various states.

Table 1: Power Consumption

Module	Status	Voltage supplied [V]	Current Consumed [mA]	Power Consumed [mW]
Sensing Circuit	No pressure	9	110	990
	Pressure	9	120	1080
Servo Motor	ON position	5	13.8	69
	OFF position	5	13.8	69
	Transition	5	180	900
Solenoid	ON position	9	1450	13050
	OFF position	9	0	0

Table 2 displays the total power consumption and an estimated run-time based on a 9V 2200 mAh battery for a single actuator.

Table 2: Total Power and Estimated run-time

Actuator	Total Power [mW]	Run time [hours]
Solenoid	6246	3.17
Servo	1122	17.64

## DISCUSSION

The results obtained demonstrate a clear difference in power consumption between the servo motor and the solenoid. Based on these results a system using a servo motor as the actuator can run approximately five times longer than a system based on a solenoid.

Choosing the servo motor as the actuator allows us to employ a smaller battery without compromising operating time. Using a smaller battery implies a slimmer lateral profile and lighter weight. These two parameters are especially significant in SCKAFO design.

The servo motor operates at 4.8 V, therefore a battery in the range of 5-8 V can be selected. Comparatively, a solenoid would require a minimum supply voltage of 9V. Many commercially available Lithium-Ion and Lithium-Polymer batteries provide supply voltages of 7.2 V – 7.4 V. Using a 7.4 V, 3300 mAh battery pack, the servo motor-based circuit (accounting for two servo motors – one on each side of the joint) would be able to run for an estimated 13.75 hours.

The choice of actuator is also dependent on the force required for actuation. The servo motor is only a viable option for low-force actuation, since its torque is limited by its size.

### **CONCLUSION**

In low actuating force applications, a servo motor solution provides considerably lower power consumption compared with a solenoid solution. For the "Ottawalk" application, a servo motor optimizes battery size without compromising operating time and allows for a smaller, more compact design.

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