A Device to Measure Joint Angles and Foot Force for Lower Extremity Force Distribution Computations

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Abstract

In rehabilitation of walking difficulties, it is vital to be aware of the distribution of the force and moment pairs faced by the lower limb extremities. The mathematical equations for numerical computation of these pairs are provided by free body diagrams that require some foot force measurements and joint/segment-tilt angle measurements as well. In this study, a device has been developed to capture the foot force and the ankle, knee and hip joint angles. The device is equipped with three accelerometers and six force sensitive resistors. The measured forces and angles are computed and next transferred to personal computer. The device is calibrated and then tested on a healthy volunteer. The test results show that the device may be used to provide valuable measurements to compute force distributions in lower extremity.

1. Introduction

Humans have engaged in walking for millions of years. In normal walking, the resulting loads are regulated so that they can be well tolerated by the joints without initiating destructive changes in the articulating cartilage. But in some people, physical loading may result in change of bone microstructure that may influence several risks for skeletal diseases such as low bone mass associated with traumatic fractures. On the other hand, in some people, weight exercises may lead to fragment dislocations and posttraumatic osteoarthritis.

Early medical diagnosis and immediate cure plays an important role in the success of rehabilitation of walking difficulties [1]. During diagnosis and cure, it is vital to be aware of the distribution of the force and moment pairs faced by the lower limb extremities. The mathematical equations for numerical computation of these pairs are already provided by free body diagrams [2]. But these diagrams all require some foot force measurements and joint/segment-tilt angle measurements as well. The angle measurements are often performed indirectly using optical motion analysis systems [3, 4]. However, these systems are expensive and have several problems such as their markers are easily obscured from vision resulting in incomplete data [5]. On the other hand, foot force measurements are commonly done using fixed force sensing platforms [6]. Recent developments in technology make body-mounted sensors available for use in both angle and force measurements [7-9]. These sensors may be accelerometers, gyrosensors, force sensors, strain gauges, inclinometers or goniometers providing various characteristics of the human walking.

In this study, a device that employs accelerometers and force sensitive resistors has been developed to capture the foot force and the ankle, knee and hip joint angles that can be used in computation of force distributions in lower extremity.

2. Developed Device

The device is equipped with six force sensors, three acceleration sensors, a microcontroller and a USB communication module. The acceleration sensors are positioned on the thigh, shank and foot to capture orientation of lower extremity body joints. The force sensors are placed beneath the foot to capture the foot contact forces: Three of them are placed on the calcaneus and others are placed under the metatarsal parts of the foot. These placements are illustrated in Figure 1.

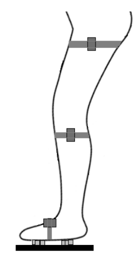

Fig. 1. Sensor placements.

The force sensors used are force sensing resistors (FSRs). These resistors are small sized, low cost and passive sensors with two terminals that decrease their inherent resistances depending on the physical forces applied. To make the FSR operational, it is connected one end to power supply and the other to a pull-down resistor to the ground. The value of this resistor is determined according to the application. When large forces are aimed, it is beneficial to use a low-value resistor that provides better sensitivity. In the device developed, 0.5" circle FSR (Pololu Inc, USA) has been employed (see Figure 2). Its resistance is very stable when the force applied is fixed and the readings are therefore very repeatable. The resistance may drop from more than 1MΩ to about 200Ω for an applied force of 10g to 10,000g. The FSR is powered with +5Vdc and connected to a 10kΩ variable resistor in series. The voltage dropping on this resistor is fed to one input of an LM324 unity-gain operational amplifier powered with +9Vdc supplied by a battery. The output of the amplifier is fed to one analogue input of microcontroller. Therefore the six FSRs of the device occupy the six analogue inputs of the microcontroller.

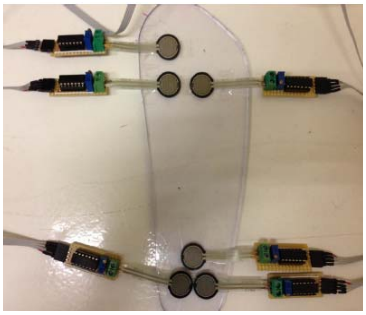

Fig. 2. FSR modules.

The acceleration sensors used are 3-axis accelerometers. Accelerometers are sensors that measure the physical acceleration experienced by an object due to inertial forces or due to mechanical excitation. The device developed houses 3-axis capacitive accelerometer with integrated voltage regulator (MMA7341L, Pololu Inc, USA [23]). The voltage regulator allows the accelerometer to accept +5Vdc and provides +3.3V to the accelerometer. The X, Y and Z outputs of the accelerometer are separate and have separate analogue voltages centered at the half of +3.3V. Positive accelerations increase above the center voltage and negative acceleration drops below the center voltage. By this, the output voltage always stays in the range of 0 to +3.3 V. This output voltage provides a way to compute the orientation of any object on which the sensor is fixed. The X-output of the sensors positioned on the thigh and the shank whereas the Y-output of the sensor positioned on the foot are connected to the three analogue inputs of the microcontroller. To provide flexible and easily replaceable connections, the sensors are soldered on specifically designed modules. Each module has two female RJ-11 jacks and two red LEDs detectable by any cam coder system when required (see Figure 3). With flexible cables, two modules are connected to each other and the last module is also connected to the base.

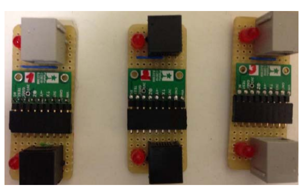

Fig. 3. Accelerometer modules.

The microcontroller of the device is a cheap, widely available and easy to use one namely PIC18F4550 (Microchip Technology, Arizona, USA). It has forty pins and thirty-two of these pins can be programmed for digital input or output use. However, thirteen of them are also able to provide analogue inputs connected to an analogue-digital convertor that performs conversion with 10-bit resolution. Two of the digital only pins namely RX and TX are dedicated to universal asynchronous receive/transmit operations.

The device is equipped with an inexpensive and easy to use serial to USB convertor (AXC-1UU, SonMicro Inc, Turkey). This convertor provides data transfers between the microcontroller and any personal computer with a free USB port. It has four terminals namely TX, RX, +5V and GND. The GND terminal works as a ground line and +5V terminal is the voltage output supplied from the personal computer to the module. TX terminal is for transmission whereas the RX terminal is for the reception of data. These two pins are connected to dedicated RX and TX pins of the microcontroller in the device providing computer connectivity.

The schematic of the device developed showing the connections of the electronic components is seen in Fig 4.

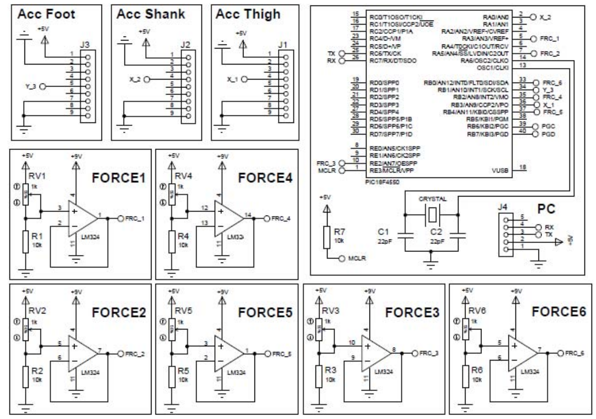

Fig. 4. Schematic of the device developed.

The microcontroller is the "brain" of the device and programmed to perform data acquisition and transmission tasks. The flowchart of the microcontroller program, written using Proton Development Suit and uploaded into the microcontroller using PicKit2 software and a programmer hardware, is presented in Figure 5.

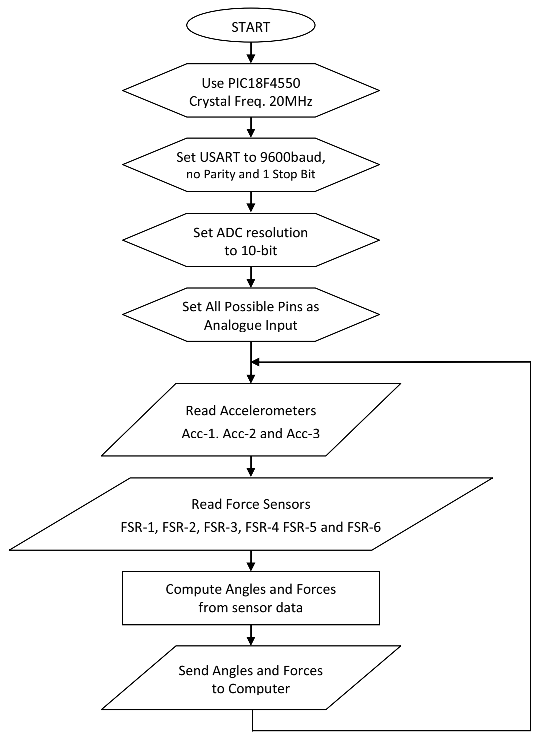

Fig. 5. Flowchart of the microcontroller program developed.

The microcontroller program is always in interaction with user interface software run on personal computer. The user interface software can be any serial communication software. However, in this study, the software embedded into Proton Development Suit has been used. Once the device is connected to the computer via its USB module, at first, the communication software is run and setup appropriately to allow data transfer (i.e. the port should be selected by the user with a speed of 9600baud, byte size of 8, no parity, 1 stop bit). After this step, the device transfers recent measurements to the user interface software simultaneously. The measurements can be copied and pasted into any spreadsheet program such as Microsoft Excel for further processing and statistical analysis.

3. Results

Before practical use, the device developed was first calibrated. To do this, known forces and orientations are applied to the sensors. The corresponding analogue-digital conversion results of the microcontroller were transferred to a personal computer via the USB module. They were used to determine transformation equations both for force and orientation.

During analogue digital conversion (ADC), the microcontroller measures the analogue voltage signal applied to its dedicated analogue input and then converts it into a digital number using a reference voltage value, V_{ref}. The analogue input may range between 0 and V_{ref} and the digital number gets value ranging from 0 to 1023 when 10-bit ADC resolution is considered. Therefore, considering the circuit connections of the device developed, one can easily determine the instantaneous resistance of a force sensitive resistor, R_{FSR} using the corresponding ADC result of the microcontroller:

$$V_{ref} \times \frac{ADC}{1023} = +5\text{V} \times \frac{10\text{k}\Omega}{10\text{k}\Omega + R_{FSR}} \quad (1)$$

Since the device uses +5V as V_{ref}, the equation above simplifies to:

$$R_{FSR} = \left(\frac{1023}{ADC} \times 10\text{k}\Omega \right) - 10\text{k}\Omega \quad (2)$$

Once R_{FSR} is determined, the force faced by the force sensitive resistor is computed in grams using

$$F_{FSR} = 1387 \times R_{FSR}^{-1.384} \quad (3)$$

The multipliers in this power equation were obtained after several experiments with known weights and curve fittings (*Pearson correlation coefficient* = 0.99). A similar approach was followed to determine the orientation in degrees. Known orientation values and corresponding ADC results were analyzed and finally a linear curve was fitted to the data giving the following equation (*Pearson correlation coefficient* = 0.99):

$$Orientation = 0.7 \times ADC - 226.8 \quad (4)$$

Practical measurements were performed from a healthy volunteer. The accelerometers were bandaged on the upper side of the femur below the hip, upper side of the tibia below knee joint and metatarsals of the volunteer's right leg. The force sensitive resistors are placed beneath the volunteer's right foot considering the highest force exerted and fixed on a flexiglass material. Measurements were done with two different protocols.

In the first protocol, the volunteer was told to keep her body position while standing and bending, respectively. For each position, ADC values generated within the microcontroller as a result of forces faced by the force resistive sensors were transferred to a personal computer using the device developed. From these values, corresponding resistance values and forces for each sensor were computed using the transformation equation derived. Tables 1a shows the forces measured.

Table 1a. Foot forces measured in grams.

	FF1	FF2	FF3	FB1	FB2	FB3	TOTAL
Standing	9997	4734	5759	9997	4405	9997	44889
Inclined	9997	8408	9401	34	91	3730	31661

Here FF and FB denote sensors positioned beneath forward and backward foot locations, respectively. On the other hand, the angles computed for the ankle, the knee and the hip are as given in Table 1b.

Table 1b. Joint angles measured in degrees.

	Hip	Knee	Ankle
Standing	2.3	5.2	-10.3
Inclined	-4.9	1.4	10.3

In the second protocol, the volunteer was told to keep her body position while standing; half sitting and sitting, respectively. Tables 2a and 2b show the foot forces and the joint angles computed for these three positions.

Table 2a. Foot forces measured in grams.

	FF1	FF2	FF3	FB1	FB2	FB3	TOTAL
Standing	9855	4468	4500	8499	8687	9511	45520
Half-Sitting	10347	3017	4005	11022	6221	9401	44013
Sitting	10096	2090	3802	11022	5308	10881	43188

Table 2b. Angles measured in degrees.

	Hip	Knee	Ankle
Standing	2.6	-11.2	-5.1
Half-Sitting	24.4	-28.9	-7.0
Sitting	31.1	-29.3	-6.1

From the tables, it is observable that while the volunteer changes position from standing to sitting, fewer forces have been applied to the hip and knee joints and the magnitude of the force is directly proportional to the joint angles. The device can provide joint angle measurements of the lower limb of healthy volunteer with stable and reasonable accuracy.

4. Conclusions

The device designed is easy to use and can be potentially adoptable in clinical practice. However, it should be noted that tests with more volunteers are need to be performed first. Force sensing resistors are quite beneficial to sense foot forces. The current device uses six FSRs placed beneath the foot considering the highest force exerted and fixed on a flexiglass material. However, the device can give more accurate force measurements with more FSRs. A Bluetooth module can also be integrated to the circuit. With the Bluetooth module, data can be transferred to a computer from a long distance without a cable connection. With dedicated graphical user interface software, the force and acceleration information, gathered from the device can be stored or traced on personal computers.

5. References

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