

Real Time Acquisition of Stump Angle as a Feedback Signal for Development of Low Cost Electronic Knee Prosthesis

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Abstract

Electronic knees provide a wide range of mobility for amputees but the high cost of these knees, due to the wide variety of sensors used and the ensuing complexity of the hardware and algorithms used there in, makes them inaccessible to most amputees in developing countries. The goal of this paper is to develop a low-cost sensor to measure the angular change of the 'stump' socket, and that of the thigh movement, with the aim of reducing the overall cost of the electronic knees. The proposed measurement system, named as Stump Angle Measurement (SAM) system, uses a low cost accelerometer, which provides a direct feedback of angular change of the thigh movement, and ultimately that of the hip joint. Preliminary results of SAM module show that the properties of feedback signal alone (amplitude and frequency) can be used to vary the speed of actuator (knee joint) resulting in a wider mobility for the amputee. The proposed system also reduces complexity of the hardware as well as algorithms used in modern electronic knee, thereby reducing the overall cost of knee prosthesis and making it more accessible to amputees in developing countries like India.

Keywords: Amputee, Electronic Knee, Prosthesis, Sensor

1. Introduction

As of 2010 estimates, around 5.5 lakh people needed lower limb prosthesis in India. For transfemoral amputees, the prosthetic knee provides the lost mobility¹. The mobility grades of these knees are classified as K1 (indoor walker), K2 (restricted outdoor walker), K3 (unrestricted outdoor walker) and K4 (unrestricted outdoor walker with rigorous demands). Low cost knees provide limited mobility whereas high cost electronic knees have been able to provide a wider range of mobility for the amputees. The expensive electronic knees make use of a feedback controlled system which helps them to achieve the higher degree of mobility along with stability in gait. More accurate gait, accurate swing phase, better control and better adaptability at walking speeds were the advantages that soon became the strong point of these electronic knees². Because of these advantages, the elec-

tronic knee has emerged as a powerful prosthesis, acting as an extension to human body structurally, neurologically and dynamically. Sensors play an important role in these systems, as they provide data from the various biomechanical actions that take place in a gait cycle. Angular movement of the joints, foot pressure, and speed of the movement of limbs are the basic factors that need to be sensed and measured. These complex feedback sensors and their associated control designs make the currently available electronic knees very costly and out of reach for most of the amputees, especially in developing and under developed nations. While most of the electronic knees will measure the knee angle for feedback sensing in variable damping knee prosthesis, it has been recently shown that the hip angle can actually provide more accurate feedback^{3,4}. The hip angle produces a periodic movement that shows a correlation with the knee angle over one gait

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cycle. Thus the measurement of the hip angle for feedback can help in achieving a normal gait cycle even at variable walking speed^{3,5}.

This paper presents a system for real time acquisition of the hip/stump angle using markedly lower number of sensors, thereby reducing the complexity and cost of an electronic knee capable of providing K1 and K2 grades of mobility. We begin with a fundamental discussion on human gait cycle in Section 2 and a discussion on historical development of electronic knee and its important components in Section 3. The design of the proposed low cost system to measure the stump angle is presented in Section 4 and the experimental performance of the ensuing prototype, including the correlation of the feedback angle obtained using the proposed Stump Angle Measurement (SAM) system with the knee angle, is presented in Section 5.

2. Human Gait

Figure 1 shows a single stride of the human gait cycle³. The gait cycle begins with heel strike of right leg and ends with heel strike of the same leg. The simplest model of walking comprises of two legs moving in sagittal plane alone.

Gait cycle consists of two phases, stance phase and swing phase. The period when both of the lower extremities are in contact with ground is called the “stance” phase and the period when only one of the extremities is in contact with the ground is called the “swing” phase. The part of the gait cycle when both the extremities are in contact with ground is called as “period of double support”. Stance phase contributes to 60% of the human gait cycle. This whole process leads the center of mass to move in an arc and the center of mass is highest at “mid stance” and lowest at “heel strike” and “toe off”.

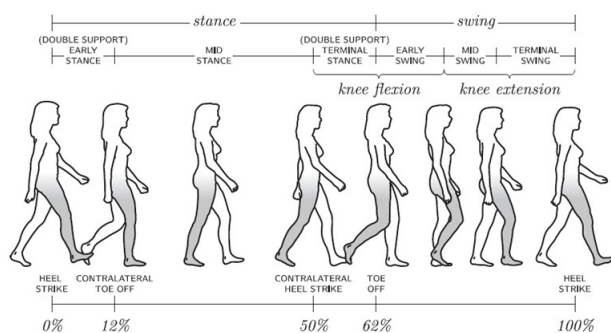


Figure 1. Dynamics of human gait over one gait cycle

3. Electronic Knee

Prosthesis industry grew steadily post World War II. Electronic actuators and EMG signals were used to achieve a volitional control of the electronic knee. It resulted in a more aesthetic gait and also provided stability over uneven terrain⁵. Attempts to improve the mobility during stance phase of level walking either focused on knee controller design or on ankle design⁶. Programmed microprocessors were used to recognize common gait patterns from the angular knee movement and feedback from strain sensors⁶. But the pre-set values in the microprocessor made it difficult to provide smooth gaits for variable speeds and walking levels of the subject⁷. Hence, a robust control system for an electronic knee which was auto-adaptive, speed adaptive and allowed stance flexion and detection of stairs was developed⁸. Variable torque Magnetorheological (MR) knee was developed giving some improvements over the electrohydraulic knee⁹⁻¹¹. Local mechanical sensing allowed the amputee to walk with an increased level of biological realism as compared to mechanical passive prosthetic knee⁹. Hybrid passive-active prosthesis added capability to walk backwards, stand up from a seat, ascend ramps and stairs ramp over ramp¹². Two series-elastic actuators along with a variable damper were used in agonist-antagonist active knee prosthesis¹³. Human like knee mechanics during steady state ground level walking were observed. Also the power consumption was modest, thereby decreasing the size of onboard batteries required for power prosthesis. A comparative study between the available electronic knee showed that the electrohydraulic driven C-Leg had clear advantages in provision of adequate swing phase flexion resistance and terminal extension damping during level walking at various speeds, especially at higher walking speeds². System for onboard charging of the batteries for a longer operating duration was developed to improve the reliability of electronic knee¹⁴. As can be seen from above, the continuous progress in the development of electronic knees has led to the development of a prosthesis device that provides a great deal of mobility and movement almost resembling that of natural gait, but this progress and development has been accompanied by an increase in complexity, and hence cost, of the device. As discussed below, based on the degree of mobility and hence, the complexity of the prosthesis, it can cost as high as \$45000, thus putting it out of reach of most amputees in developing or underdeveloped nations.

Sensors form the key component of any feedback system, and hence are also a key component of any electronic knee. Feedback signals from knee, ankle, hip and feet help the control system achieve a smoother gait. The complexity of the system design depends upon the number of sensing units used and the algorithms involved. The primary sensors generally used in an electronic knee are as follows.

3.1 Angle Sensor

Direct measurement of the angle between two links can be done with the aid of a potentiometer, optical encoder or magnetic encoder attached at a pivotal point. Indirect measurement can also be done by using an accelerometer to measure the tilt and determine the angular change at the joint. An angle sensor is used to measure the hip angle and knee angle in sagittal plane.

3.2 Torque Sensor

Human gait involves weight loading activity at stance phase of the gait (Figure 1). Torque sensors are used in magnetorheological knees to detect the knee torque. Torque sensor can either be bulky or expensive. Torque feedback is necessary to achieve a better stability of the gait.

3.3 Foot Pressure Sensor

The foot pressure/contact sensor provides feedback on heel strike and toe off event in the gait. Like torque feedback, the feedback from foot position helps to achieve better stability during the dynamic gait cycle.

Electronic knees also make use of various actuators to carry out the knee action. These include mainly electrohydraulic, pneumatic, magnetorheological or linear actuators. Electrohydraulic actuators offer better functional and safety related advantages over the other actuators used in electronic knees¹. Clinical effectiveness of the prosthetic component is dependent on the reliability of the different functions offered to the amputee in daily life. The cost factor of electronic knee varies greatly depending upon the type of actuator used.

4. Design of the Proposed Low Cost Electronic Knee

There are various electronic knees commercially available for the amputees, namely hydraulic knee, pneumatic knee

and MR knee. These products provide wider mobility grades for the amputees. The accuracy and efficient working of these electronic knees depends largely on the feedback systems incorporated in these designs. The complexity of the hardware and the associated algorithms make these devices highly expensive, with the costs going as high as \$45000, and even a basic electronic knee can cost around \$12000¹⁵. To develop a cost effective electronic knee, the development of sensing modality should comprise of minimal hardware and a less complex yet reliable algorithm.

4.1 Technology Principle

An electronic knee is basically a feedback control system with three major components: Sensor system, microcontroller unit and an actuator. The actuator helps to provide automatic flexion and extension as well as damping while loading of the body weight, hence maintaining a proper and stable gait even for varying walking speeds. Figure 2, generated using OpenSIM software, shows the degree of variations of the hip and joints over one gait cycle. The knee angle shows a bigger variation when the stance phase changes to swing phase and provides information about the flexion angle of the prosthesis. Present electronic knees stress on knee angle variations and load at the knee joint as feedback signal to the controller assembly. Accelerometer, magnetic encoders and load sensors are used for this purpose³. A higher sampling rate of these feedback signals is desired which further adds to the complexity of hardware as well as the code. Electrogoniometer is also used to measure knee angle externally¹⁵. The knee angle feedback provides information about the flexion

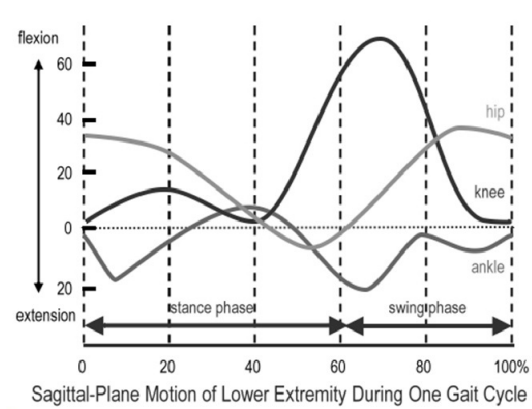


Figure 2. The angular changes at the lower extremity over one gait cycle

angle of the prosthesis. The fact that in above knee amputees the knee is absent implies that the system has to rely on indirect measurement of the knee angle in order to obtain an accurate feedback. The prosthesis thus requires more complex algorithms and has to depend on more than one sensor for reliability.

The prosthesis thus requires more complex algorithms and depends on feedback from multiple sensors¹⁶. Current prosthesis use this to detect the change of events from stance to swing phase^{11,16}.

The movement of the thigh also helps in predicting the gait cycle, thereby helping as the major feedback for the low cost electronic knee development. The hip/stump provides a volitional control, and can be used as an alternative to predicting the knee angle, and may easily be used to detect the gait movement³. The hip angle variations are fairly smooth over the whole gait cycle and the rate of change of hip angle can be used to detect the walking speed as well as the standing and sitting condition. To lower the cost of the electronic knee, lesser number of sensors with reliable feedback should be used to provide at least the basic K1 and K2 mobility grades. SAM (stump angle measurement) system proposes use of an accelerometer to measure the hip angle as well as the frequency of limb movement. This helps in maintaining a simple code and faster learning mechanism for the electronic knee.

In the SAM module design presented in this paper, thigh angle sensor is mounted on the stump externally (Figure 3). This helps to monitor the two parameters directly associated with the gait – knee angle, as described above, and walking speed. The swinging movement of the thigh provides a feedback signal that is used to calculate the walking speed, as well as the movement of the limb in sagittal plane, which is the primary area of interest. The rate of change of output voltage of the sensor (diff) helps to estimate the walking speed of the amputee. A majority of positive values of this differential voltage implies the stance phase whereas a majority of negative values implies the swing phase of the gait cycle.

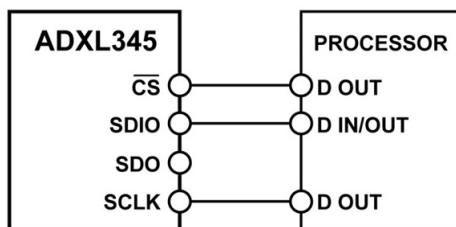


Figure 3. Interfacing diagram of accelerometer and microcontroller

4.2 Stump Angle Sensor

The accelerometer ADXL345 (Analog Devices), which meets the availability, voltage and cost requirements, is capable of measuring static acceleration of gravity in tilt sensing measurement as well as the dynamic acceleration resulting from motion, shock and vibration. As explained earlier, it is mounted on the stump directly to detect the thigh movement in sagittal plane. The accelerometer is used to calculate/measure the tilt (angular) changes in sagittal plane. ADXL 335 is used for dual-axis tilt calculation as it provides higher resolution as compared to single-axis tilt sensing. The three major benefits of using a second axis of inclination are constant sensitivity, reduced dependence on alignment plane of gravity and complete 360 degree tilt sensing. Output of the sensor is used to make corrective changes in the actuator. Thus flexion and extension actions (replicating the knee) can be easily achieved, even at various walking speeds. The angular changes of the hip can thus be used to bring out flexion and extension in lower limb using any electronic actuator (linear electric, electro-pneumatic and electrohydraulic). Whenever the Range of Motion (ROM) exceeds the above values, actions like sitting and standing up can be predicted.

4.3 Interfacing of Sensor with Microcontroller

LPC 21xx was used as the microcontroller for prototype development. Figure 3 shows the interfacing between the accelerometer and the microcontroller. The output amplitude of the sensor (accelerometer) does not need any amplification and is sufficient to drive the input of this microcontroller. The built-in ADC is used to further process the output from the accelerometer. Signal conditioning can include low pass filtering to remove high frequency noise content. The design presented herein does not include any low pass filter. The sensitivity required in the input measurement is kept at medium to avoid high frequency noise generated due to human errors.

5. Implementation and Testing of Stump Angle Measurement System

5.1 Stump Angle Measurement

The Stump Angle Measurement (SAM) system incorporates an accelerometer, as described in the previous section,

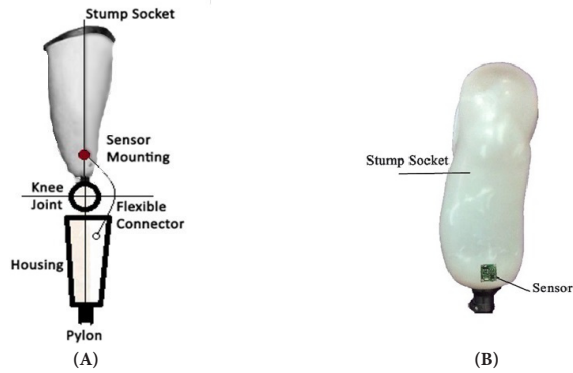


Figure 4. Placement of the knee angle sensor (A) proposed system (B) sensor mounted on actual stump socket of an amputee

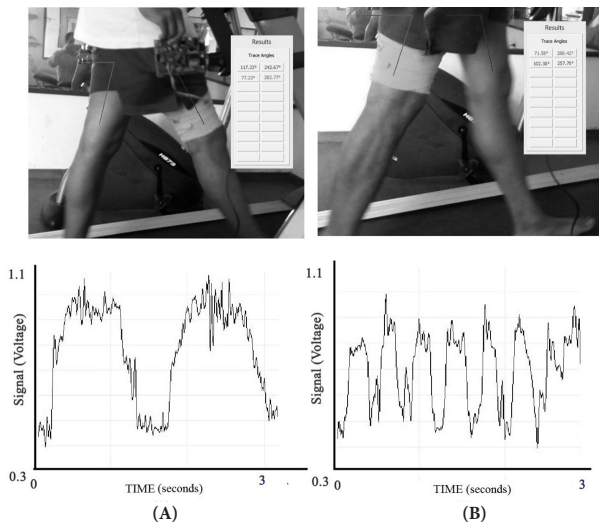


Figure 5. Testing the SAM system. Video analysis showing the angle at the hip joint

which in turn is connected to the microcontroller with a flexible wire connector. The prototype stump socket was designed in collaboration with Sancheti Hospital, Pune. The placing of the accelerometer on the stump socket is shown in Figure 4.

For testing purposes, the SAM system is attached to the thigh of a sound person, via an orthotic belt, as shown in Figure 5. The subject was then made to walk on a treadmill.

A periodic waveform is obtained as the sensor output, coinciding with the periodic walking gait of the subject. Figures 5(a) and 5(b) show the periodic sensor output waveforms thus obtained, corresponding to slower and faster walking speeds respectively.

These output waveforms give the required tilt values in two dimensional plane, here the sagittal plane.

5.2 SAM Module Testing

The SAM module circuit was tested under static i.e., standing and sitting and dynamic i.e., walking conditions. Initial tests were performed to check for the precision and stability of the circuitry in a changing environment.

For measurement under dynamic conditions, the sensor was attached to the thigh of the subject and he was made to walk at variable speeds on a treadmill. SAM system output values were taken at different points of the gait cycle i.e., heel strike, swing phase (of other leg) and toe off events. For the static conditions of standing and sitting, the circuit was tested for baseline drifts over a period of 10 seconds. Figure 6 shows the output response of the accelerometer obtained during static and dynamic conditions. Deviation during fast walking is due to vibrations and physical noise and can be reduced using filters. This signal works a reliable feedback signal to the controller unit. It can be observed that the output shows very little baseline drift. The root mean square error of the output signal at static conditions was calculated to be 0.003V.

Table 1 shows the comparison of the output values thus obtained, with the corresponding values obtained via simulation using SIMM software and Video analysis software (Quintic Biomechanics) at similar stages in human gait cycle. It can be observed that the SAM system values are in good agreement with the simulation and video analysis values.

The baseline drift in dynamic environment was more, as compared to that obtained during static conditions, but still within acceptable limits. This test was repeated on the same subject at various instants to check for the stability of the system. The RMSE values thus obtained are between 0.003V and 0.005V, thus demonstrating that the SAM system shows sufficient sensitivity and stability and can provide a reliable feedback for the electronic knee joints.

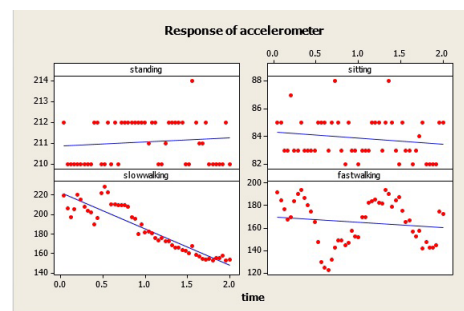


Figure 6. Output response of the accelerometer in static (standing and sitting) and dynamic (slow and fast walking) conditions.

Table 1. Comparing the hip joint angle: Simulation, video analysis and accelerometer output

Level of Walking	Gait event	Simulation values	Video Analysis Values	SAM system o/p (converted in degrees)
		(degrees)	(degrees)	(degrees)
Slow Walking	Heel strike	31.2	26.15	32
	Swing Phase(other leg)	27.5	22.77	23.75
	Toe off	-4.5	-2.17	-3.75
Fast Walking	Heel strike	37.2	29.31	33.25
	Swing Phase(other leg)	28.3	23.43	23.75
	Toe off	-7.5	-4.49	-4.75

The tilt values thus obtained from the SAM module can be compared with the pre-set lookup values determined using the data from simulation results shown in Figure 2. With the addition of foot pressure and load sensors, a corrective action could be taken to bring out extension and flexion action at the knee. The development and testing of such a system, with the addition and interfacing of pressure and load sensors, would be the subject of future work.

6. Conclusion and Future Work

We present the design a low-cost yet sensitive and stable module, Stump Angle Measurement (SAM) system, for measurement of the hip angle in the sagittal plane as part of an effort to develop a low-cost electronic knee, that bridges the economic as well as the functional gap that currently exists between high end mechanical knees and the highly expensive basic electronic knees. An accelerometer is connected to the stump socket to directly measure the stump/hip angle, in contrast to employing the commonly used magnetic and optical encoders and electrogoniometers which require the use of additional interface circuitry, thereby reducing the overall cost and complexity of the circuit.

Accelerometer ADXL345 was used for construction of the SAM module prototype. The system was tested by connecting it to the hip of the test subject and measuring the sensor output i.e., hip angle in static as well as dynamic conditions. The obtained results correlate well with the output obtained from simulation analysis and also with the results obtained from Video Analysis software. The total observed angular range of motion of hip joint in sagittal plane, over one gait cycle, agrees well with the results reported by. Even with the absence of a signal condition-

ing unit, the results obtained show less noise interference, except for the high frequency noise component present due to the sensitivity of the accelerometer and to some extent, the placement of the sensor on the subject. The sensor was placed at axial point on the thigh, and it was found that greater the distance from the hip joint, higher the output amplitude. The cost of the accelerometer is less than \$10 and the entire cost of the SAM module is ~\$400, thus helping us realize our objective of designing a low cost stump angle measurement system.

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