# DEVELOPMENT OF STRATHCLYDE UNIVERSITY DATA LOGGING SYSTEM (SUDALS) FOR USE WITH FLEXIBLE ELECTROGONIOMETERS

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Abstract: We have developed a 6 channel battery operated remote control microprocessor based system that collects data from flexible electrogoniometers and force sensing resistors attached to the lower extremities of the body. During functional activities, the user-friendly system stores the data from these transducers and transfers the same to a PC at the end of the recording period via a bluetooth connection. Software on the PC then displays the angular displacement and allows visual inspection of the entire sequence of recordings or particular events of interest. This system was tested on 10 normal subjects and the pattern pertaining to the flexion/extension of knee during range of activities of daily living (ADL) such as walking, ascending and descending stairs, in and out of a chair and deep squatting were recorded and found to be reproducible and similar to those reported in the literature.

## 1 INTRODUCTION

Normal lower limb activity and goal directed movements are essential for the well-being of an individual. However, such movements and efficient functioning of the lower limb can be seriously affected for a variety of reasons and one such common cause is Osteoarthritis. This degenerative joint disorder is often disabling and is characterized by pain and physical limitation. (Rowe et al, 2005). As a result, functions of lower limb are affected, causing individuals to have problems with ADL such as; walking, climbing stairs, getting in and out of chair, getting in and out of bath etc. At this point of time, rehabilitation and health care professionals play a very crucial role by improving the functional ability of their clients. Periodic assessment of the individuals is necessary to aid the health professions in assessing efficiency of their interventions. Currently, two types of assessment techniques are available for this purpose: questionnaire based assessment and assessment based on clinical gait analysis.

The former technique makes use of knee scoring questionnaires such as the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) and Knee Society Clinical Rating System. (Rowe et al, 2005). Even though, these questionnaires are popular, easy to administer and characterize the overall performance of an individual, research reveals that they are highly subjective and do little to reveal any objective information regarding the actual restoration of the knee function required by an individual to perform ADL.

On the other hand, clinical gait analysis is an expensive and time consuming process. (Rowe et al, 2005). Alternatively, researchers have started using electrogoniometry to record the dynamic knee joint movement during a range of functional activities due to its simpler, cheaper and reproducible nature. (Rowe et al, 2005, Rowe et al, 2001) Mostly, such body mounted transducers are used in combination with information storage devices known as "Data Loggers". (Rowe et al, 2005).The role of these devices is not merely to store the data collected from these transducers but also to convert the signals obtained from the transducers to an understandable form. Many such devices have been developed in the past and are also being currently used along with a wide range of transducers such as flexible electrogoniometers, accelerometers and strain


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gauges for mobility assessment, recording of plantar pressure etc. (Zhu et al, 1991). Wireless communication is finding its way into various medical technological applications (Zhang.Z & Liu.P, 2004), but most data loggers remain hardwired. It was the premise of this work that the data logger currently used with flexible electrogoniometers needs further improvement in functionality so that, the process of collecting a large stream of data and extracting the relevant sections could be carried out more efficiently. Further, such a system should be able to be used by any allied health professional in a multi centered clinical trial evaluating post-operative rehabilitation. The lack of such a system merits the development of a user friendly system, whereby pushing a button would start, stop, collect multiple data sets and transmit the same without any physical contact between the subject and the operator.

We have developed a portable, battery operated, remote control microprocessor based system that allows recording, deleting and transmitting the data obtained from two flexible electrogoniometers and four force sensing resistors. The data is stored in static random access memory (SRAM) and can subsequently be transferred via Bluetooth to a PC which processes and analyzes the data.

# 2 METHOD

## 2.1 Overall System

The flexible electrogoniometer consists of a strain gauged shim (a thin flexible strip) which runs the length of the device. Damage to the device and injury to the test subjects is prevented by enclosing the shim in a spring. To facilitate the attachment of device to the subjects, two light weight plastic plates are fastened to the ends of the shim. The resulting transducer does not have a specific centre of rotation and is flexible in both medio-lateral and anterior-posterior directions. Each electrogoniometer was attached using double sided medical grade tape laterally to the shank and thigh of individuals via two flexible plastic strips – adjusted to the length of their shank and thigh. In addition to this, light weight force sensing resistors (FSR) or footswitches were attached to the first metatarsal area of the toe and to the heel for marking the events by indicating the contact between the foot and the floor. Since the transducer was mounted in the sagittal plane of the knee, the output of the device represented the flexion-extension angle of the knee. Both the electrogoniometers and footswitches were interfaced to SUDALS via thin flexible cables.

## 2.2 Hardware Design

The entire prototype was built on an evaluation board – Eval ADUC7026 which consists of a 12 bit successive approximation type Analog to Digital converter (ADC), with an on chip 32 bit microcontroller. The microcontroller provides both high performance and low power consumption. The microcontroller has several on chip facilities including programmable watchdog timer and 12 channel multiplexer. Hence, an additional multiplexer or a sample or hold circuit was not used in our system. The ADC chip analogue input range is 0 to 2.5V DC, whereas, the output of the flexible electrogoniometer is a differential voltage. As a result, the voltage signals from these transducers were conditioned using high precision Instrumentation amplifier (INA101) with suitable gain resistors so as to make these signals compatible with the input range of ADC. Due to the low temperature drift feature of this amplifier, the system will not be significantly affected by ambient temperature. Six 1.2V alkaline AA batteries are used for powering the evaluation board, which is regulated via an on chip voltage regulator to 3.3V. This is used to drive the digital side of the board and the same voltage is being filtered by the on chip features to drive the analog side of the board. In addition to this, the output from the batteries is stepped down to +/- 5V via DC-DC converter to power the amplifiers, the transducers and other signal conditioning components on board. The data from two flexible electrogoniometers and from the four force sensing resistors are sampled at 50 HZ and the digital values are stored in a 32KB x 16 static RAM – an external memory chip interfaced via the footprint provided on the evaluation board. To the same memory, the data from the FSR channels are compressed to on/off data and saved as a single byte.

The data from the external memory is transferred to a personal computer via a bluetooth transmitter (HDWBTRS232 – wireless RS232 Transceiver) interfaced to the Eval ADUC7026 via the universal asynchronous transmitter (UART) terminal provided on board and a transmitter line driver ADM202. The transmitter works on a voltage range of 5V-9V DC, which is being provided using the same AA batteries on board. Due to high power draining application (wireless transmission), batteries chosen for the operation of this system has a high power rating of

2400 mah. A Baud rate of 19200 was used to transmit the collected data to a personal computer (PC) in less than a minute. At the PC end a software code written in MATLAB is used to receive the transmitted data and store the data in the format of excel files which are analyzed further depending upon the user requirement. We simultaneously measured the knee flexion / extension angles during activities of daily living such as; walking, ascending and descending the stairs, sitting in and out of a chair and deep squatting and established that the portable system could faithfully reproduce the signal. The obtained data is analyzed for maximum and minimum knee flexion / extension during these activities and the results are compared against the normal knee range of motion during these activities published in the literature. The overall block diagram of the system is as shown in Figure 1.

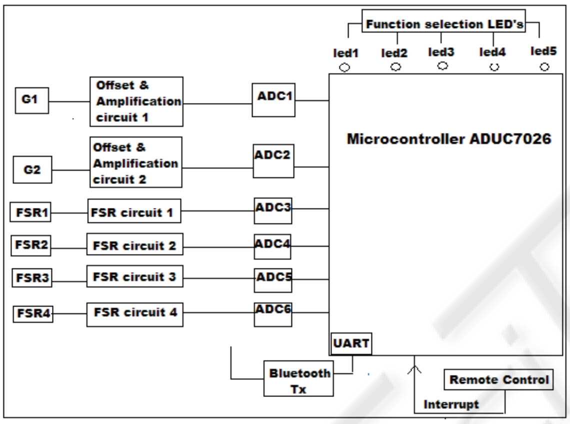


Figure 1: System block diagram.

## 2.3 System Functionality

The system is aimed to perform 5 functions corresponding to data collection. These include; recording a test, scrapping a failed test, transmitting the collected data from the electrogoniometers and footswitches and resetting the entire system. In addition to this, the system also facilitates zeroing of the electrogoniometers prior to each recording depending upon the user requirements. This is accomplished by making use of an Operational amplifier 3240 at the hardware end.

Initially, when the system is connected to the sensors and switched on, the system is ready to zero the sensors and to record the data corresponding to the knee flexion/extension. Once, a singe recording is completed, then the system facilitates the user to make use of other functions such as; scrapping the recorded data 'if needed', else transmit the collected data via wireless and reset the entire system for next set of data collection. Each of these above mentioned functions can be accomplished by providing interrupt service routines (ISR) to the microcontroller to start or stop that specific function via an Infra red remote transmitter and receiver interfaced with the microcontroller, when the LED corresponding to that function illuminates. Since, all these functions operate within a loop arrangement; the user can perform single recording or multiple recording, store it in the external memory and then transmit it to the PC via wireless. The functional flow chart of this system is as shown in Figure 2.

## 2.4 System Evaluation

The system was evaluated by carrying out a pilot study, during which the data pertaining to the flexion/extension of the knee of the 10 young normal healthy subjects who volunteered for this study was collected via the flexible electrogoniometer interfaced with this portable unit. All the 10 subjects were asked to perform the following 6 activities – Walking, In and Out of a Chair, Stair ascent, Stair descend and deep squat corresponding to daily living.

Start and stop commands were given at the beginning and completion of each task and the subjects were asked to repeat these tasks three times for reproducibility and repeatability purposes. Further, the event marking was taken into account by the FSR's attached to the toes and heels of each subject.

After data collection a 4$^{th}$ order low pass Butterworth filter at a cut-off frequency of 6 Hz was used to eliminate the noise present in the data. The data collected during these activities were averaged for each subject individually and were analyzed for maximum and minimum knee flexion. The excursion of the knee during these activities for each individual was obtained by calculating the difference between the maximum angle and minimum angle. This procedure was carried out for both the left and right knees and was then averaged to provide the group mean. The excursion of the knees from SUDALS is as shown in Table 1. Table 2 shows the maximum knee flexion angle reached during each of these ADL. The results were compared against the values published in the literature as shown in Table 3.

The mean normalized gait cycle obtained by SUDALS during the experimentation is shown in figure3.

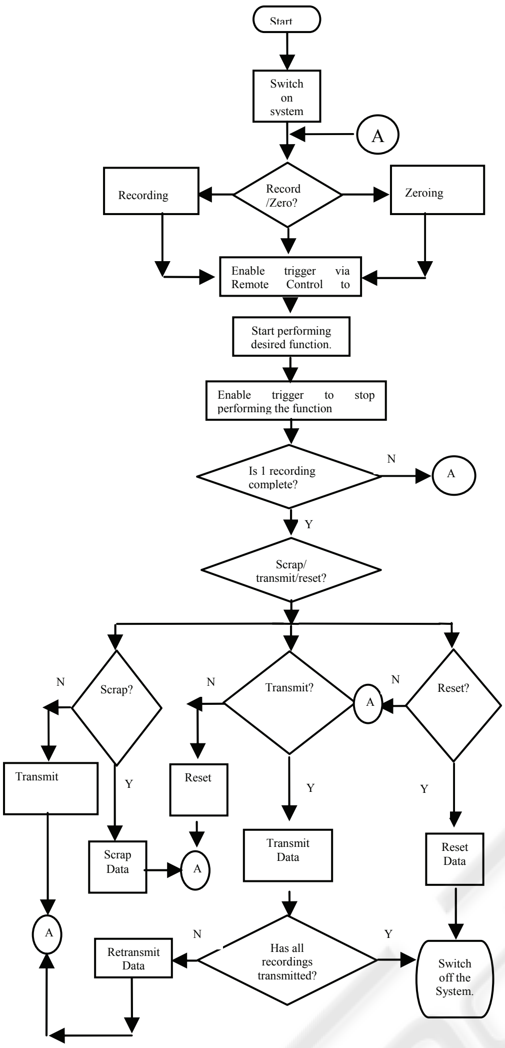


Figure 2: System functional flowchart.

Table 1: Knee ROM during ADL from SUDALS.

| ADL | SUDALS - excursion | |
|---|---|---|
| | Left Knee | Right Knee |
| Gait | 66.0° | 66.4° |
| Stair up | 71.3° | 71.8° |
| Stair Down | 69.7° | 61.5° |
| Chair in | 101.7° | 100.9° |
| Chair Out | 102.4° | 107.1° |
| Squat | 116.4° | 111.7° |

Table 2: Knee Flexion angles during ADL from SUDALS.

| ADL | SUDALS - Maximum Knee Flexion (degrees) | |
|---|---|---|
| | Right Knee - ±1SD | Left Knee - ±1SD |
| Gait | 64.9 | 62.6 |
| Stair up | 88.8 | 82.7 |
| Stair Down | 80.2 | 79.5 |
| Chair In | 105.6 | 105.8 |
| Chair Out | 112.3 | 103.5 |
| Squat | 115.6 | 121.2 |

Table 3: Knee flexion angles from literature.

| | Gait | Stair up | Stair Down | Chair In | Chair Out |
|---|---|---|---|---|---|
| Jevsevar.D.S et al 1993. | 63.3° ± 8.1° | 91.8° ±10.4° | 86.1° ± 5.5° | - | 90.05° ±8.9° |
| Costigan et al - 2002. | - | 90°± 1 SD | - | - | - |
| Lark..S.D et al - 2004 | - | - | > 120° | - | - |
| Kettlekamp et al - 1970 | 67.4° | - | - | - | - |
| Andriacchi et al - 1980 | - | 73.4° | - | 81.6° | - |
| Protopapadakki et al 2007. | - | 93.92° ± 7.40° | - | 90.52° ± 7.11° | - |
| Huddleston et al 2006. | - | - | - | - | 120° - 160° |

## 2.5 Discussion

The system described here was able to record, store and transmit the data corresponding to the ADL.

Our results indicate that, the average maximum knee flexion angle for all the 10 subjects during the above mentioned ADL lies within the results published in the literature as shown in Table3.

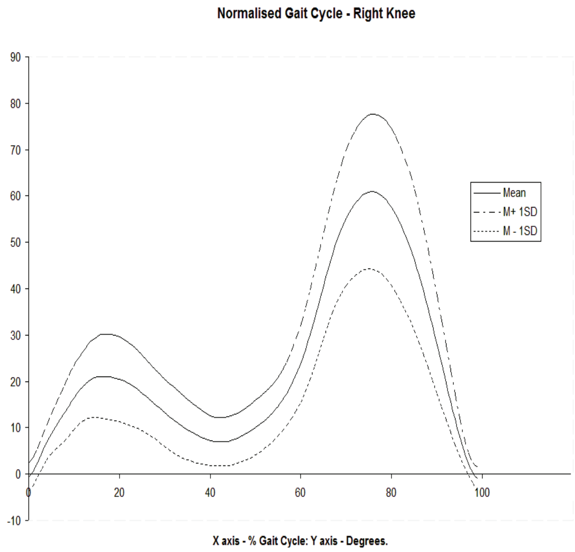

Figure 3: Normalized average Gait Cycle.

However, the knee flexion angles obtained during squatting seem to be a little lower than the values published in the literature. One of the possible reasons for this could be the way in which the subjects performed this activity. Though, the subjects were shown what they were suppose to perform during the process of recording, certain subjects were unable to completely squat as it was a difficult task and required a lot of effort. Due to this, certain subjects performed half squat instead of a complete squat. As a result, the knee flexion angle recorded during this activity would be different from those reported by Wyss.U et al - 2003, where the subjects have performed a complete squat. Moreover, most of the authors, other than Huddleston.J et al - 2006, haven't used flexible electrogoniometer for measuring the knee flexion angles. At the same time, though these authors have reported the maximum knee flexion angles during ADL, none of them have reported the knee excursion of the subjects during these activities. On the other hand, most of the studies by Rowe.P.J et al – 2005, have reported the obtained knee excursion during various ADL, but most of his studies are concerned with the follow-up of TKA and elderly population. Hence, the results from this study of young healthy subjects were unable to be compared with those published by Rowe et al. Most of the day to day activities can be accomplished in less than a minute.

Evidently, during our experimentation, we noticed that the time taken to complete a single trial of all the above mentioned six ADL by all the subjects was less than a minute. Henceforth, despite the usage of a 512 KB SRAM as prescribed by the manufacturers of the evaluation board, we were able to record, store and transmit the biomechanical motions corresponding to six ADL with a little difficulty. This ability to record, store and then rapidly transmit the data facilitates data collection in a free living environment and enables the user to check whether the data recorded is reliable or not. In this case, the user can re-record the activity immediately unlike the commercially available Biometrics data acquisition systems with flash memory, where the user has to wait until the entire data collection process is completed to check for reliability and reproducibility of the data.

Currently, most of the portable data acquisition systems that are used with flexible electrogoniometer do not facilitate remote control operation. Consequently, every time the users have to physically change the settings of the data logger such as starting, stopping or resetting; once it's being worn by the subjects. However, we were able to control the entire process of data collection by staying at a convenient distance of less than a foot from the subjects. This would not only avoid any physical contact with the subjects, but at the same time, it would also minimize the degree of inconvenience to the subjects. None of our subjects reported any discomfort with SUDALS during the process of data collection. Due to high power draining application (wireless transmission of data), we have used 6 x 1.2 V AA high wattage batteries of 2400 mah in our system. Further, unlike the commercially available systems, SUDAL also has a provision similar to the car battery charger for recharging the batteries without removing them from the system. Charging these batteries for 2 hours enables us to use the system for more than 8 hours. Though our system doesn't facilitate real time waveform display, simultaneous data collection and transmission almost replicates those systems with real time waveform display. Thus, the users would be able to analyze the transmitted data stored in the form of excel files. Figure 4 shows the usage of SUDALS in an experimental set up.

# 3 CONCLUSIONS

In summary, the system worked without any technical difficulties and was able to accurately measure the knee flexion/extension during activities of daily living in healthy subjects. The results of the present study in conjunction with the literature review support the use of SUDALS together with flexible electrogoniometers as a complimentary instrument along with other functional assessment questionnaires in providing objective data to the clinicians. This would in turn help the rehabilitation professionals to improve their intervention. In the future, we plan to validate SUDALS against vicon system (Gold standard) and use the system to evaluate the functional outcomes of patients following Total Knee Arthroplasty. The system can be further developed to interface with mobile devices and provide real time display of data collected. Thus, a flexible, compact, powerful and portable multi-channel data collecting system of flexible electrogoniometry has been designed and developed.

Figure 4: SUDALS mounted on a subject during experimentation.


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