Development and Validation of a user friendly data logger (SUDALS) for use with flexible electrogoniometers to measure joint movement in clinical trials

VIVEK.P.INDRAMOHAN, G.VALSAN and PHILIP.J.ROWE*

University of Strathclyde, Bioengineering Unit, Wolfson Centre, Glasgow, G4 0NW UK.

*Corresponding author. Email: philip.rowe@strath.ac.uk

Abstract

Objective – Our aim was to develop and validate a user friendly data logger system (SUDALS) for use with flexible electrogoniometry.

Methods – Data pertaining to flexion/ extension of the knee from 10 normal subjects was collected during a range of activities of daily living (ADL) such as; walking, ascending and descending stairs, in and out of a chair and deep squatting. The accuracy, reliability and reproducibility of the data from SUDALS were verified by comparing against the data simultaneously collected from the VICON system.

Results – The results of these studies indicate that the SUDALS together with flexible electrogoniometers is able to produce stable, precise, accurate and repeatable knee flexion/extension angles with little variation existing between the data produced by the SUDALS, the Vicon system and that reported in the literature.

Conclusion – The SUDALS together with flexible electrogoniometers is a useful clinical tool, capable of recording knee flexion/extension angles accurately during ADL.

Keywords: Flexible electrogoniometer, SUDALS, activities of daily living (ADL), knee flexion/ extension, knee excursion, concurrent validity.

1 Introduction

Following total knee arthroplasty (TKA), rehabilitation and health care professionals aim to restore the joint motion of their clients by promoting rehabilitation of functional activities [1]. Active and passive joint range measurements using manual goniometry are used to indicate the status of the joint. These measures have been reported to have poor inter-tester reliability and concurrent validity. Further, such measurements recorded in a non-weight bearing conditions do not reveal any information regarding the actual joint range of motion that would be exhibited by individuals during ADL. For this, the motion of the knee must be monitored during various functional activities performed by individuals during daily living, which in turn provides information about the dynamic behaviour of the joint. The outcome of such assessments would be useful in meeting the increasing demand for evidence based practice and evaluating the efficiency of the interventions. Many researchers have used motion analysis within the gait laboratory as a conventional gold standard for ascertaining the kinematic behaviour of a joint during various day to day activities [2]. However, research reveals that this technique is an expensive and time consuming process. [3] Alternatively, researchers have started using flexible electrogoniometry to record dynamic knee joint movements during a range of functional activities. Over the past decade many researchers have used this method for various applications and the literature reports that this method is currently gaining in popularity due to its simple, cheap and reproducible nature [1, 3]. Such body mounted transducers are used in combination with information storage devices called ‘Data Loggers’. We have developed a user friendly system of flexible electrogoniometry known as Strathclyde University Data logging System (SUDALS), which we consider to be suitable for routine functional testing of patients following TKA.

2 Methods

SUDALS is a 6 channel; battery operated remote control, microprocessor based, system capable of collecting data from flexible electrogoniometers and force sensing resistors. 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 which controls the overall functioning of the data logger via an on chip resident program. During functional activities, the user-friendly system records and stores the data from the transducers. It can be repeatedly started and stopped using a key fob. At the end of recording the system transfers the data to a PC via a bluetooth connection again by simply by using the key fob. Software on the PC then displays the angular displacement and allows visual inspection of the entire sequence of recordings or particular events of interest prior to further data analysis. As the input voltage required by the A/D converter was in the range of 0 to 2.5 volts, the differential output of the electrogoniometer was amplified prior to data conversion. In order to account for inter goniometers differences and the possibility that the goniometer may be attached so that it is not straight in the neutral position, appropriate signal conditioning was used to set the output of the amplifier near to the bottom of the amplifier near to the bottom of the A/D range prior to the data recording. This zeroing procedure was again achieved by pressing the key fob and with the tested joint in neutral position.

2.1 Calibration and tests for Accuracy and Precision

In order to calibrate the device, an electrogoniometer was plugged into the SUDALS system and was attached to the arms of a 350 mm plastic protractor using micropore around the end plate and the protractor arm. The A/D converter transforms the electrical voltage from the electrogoniometer into a computer number ranging from 0 computer units equivalent to 0 volts to 4095 computer units equivalent to 2.5 volts. With this arrangement, the electrogoniometer was displaced through a range of angles varying from 0° to 150° back through 0° to – 150° and back to 0° in ten degree increments using the protractor. The output from the electrogoniometer was recorded for 6 seconds at 50 Hz in each position yielding 300 readings. The initial and the final 50 data points were not considered and of the 300 data points obtained, the mean of 200 readings was calculated. These values were used to calibrate the system. SUDALS has 2 analog channels to which the electrogoniometer can be connected. Hence, the above procedure was repeated with both the channels and using 3 different electrogoniometers (SG150 manufactured by Biometrics Ltd Gwent) and on two different occasions to determine the influence of channel, electrogoniometer and time on the recorded angular displacements. To calibrate the system the applied input angle in degrees(X) from the first set of data was related to the recorded output in computer units(Y) using regression analysis. These values were then used to convert the data from subsequent test from computer units to angles. The calibration plots are as shown in **figure 1a** and **figure 1b**. The line of best fit through this data for all the three electrogoniometers, when connected to each of the channels was obtained individually and then averaged to obtain slope and constant values for channel 1 and 2. Following an interval of 1 hour, the above procedure was repeated and the data obtained from this trial was used to determine the accuracy of the system using the mean values and the precision of the system by calculating the standard deviation of the 200 readings around the mean value for that increment.

2.2 Test for reliability and reproducibility: Reliability and reproducibility was tested by carrying out a pilot study with 10 young normal healthy subjects (age range 24 to 30 years) who volunteered for this study. Prior to the experiments, ethical approval was obtained from University of Strathclyde ethical committee. The data pertaining to the flexion/extension of the knee of the subjects was collected using two flexible electrogoniometer interfaced with SUDALS system. To facilitate the attachment of device to the subjects, two light weight plastic plates were fastened to the ends of the instrument. 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. Further, to reduce the effect of the soft tissue movement between the leg and plastic strips and to hold the electrogoniometers firmly in place, Velcro straps were used. In addition to this, light weight force sensing resistors (FSR) acting as footswitches were attached to the first metatarsal area of the toe and to the heel for marking the gait cycle events by indicating the contact between the foot and the floor. Since the electrogoniometers were mounted in the sagittal plane of the knees, the output of the device represented the flexion-extension angle of the knees. Both the electrogoniometers and footswitches were interfaced to SUDALS via thin flexible cables. The data collected and transmitted using this unit was then filtered using a 4^{th} order low pass Butterworth filter at a cut-off frequency of 6 Hz to eliminate any noise present in the data. All the 10 subjects were asked to perform the following 6 activities

– Walking, In and Out of a Chair, Stair ascent, Stair descent and a 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 reasons. The data collected during these activities were averaged for each subject individually and were analyzed for maximum and minimum knee angle. The excursion (maximum knee angle – minimum knee angle) 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 average time normalized gait cycle obtained by SUDALS during stand to sit activity by the group is shown in **figure 2a** and **figure 2b** shows the time normalized individual gait cycles from a single subject during the repeat sessions of this activity.

2.3 Test for Concurrent validity: Test for concurrent validity was carried out by simultaneously recording the knee movement during gait using a 7 camera Vicon movement analysis system and flexible electrogoniometry. Three normal subjects (one male and two females, age range 24 to 30 years) were recruited for this study. A set of retro-reflective markers were attached to the hip, thighs, knees, shanks and feet for gait analysis and the user-friendly system of electrogoniometry was attached to the volunteers as explained above. Both the systems were synchronized by attaching 4 FSR’s (2 FSR’S were attached to the toe and another 2 were attached to the heel) to one foot (either right or left) of the subjects. Whereby, one pair of foot switches were connected to the vicon and the other pair were connected to the SUDALS. The subjects were asked to start walking using the foot in which all the four FSR’s were attached and the data pertaining to the flexion/extension of the knee was recorded from both the systems simultaneously during six free-speed walks across a 7-metre section of level vinyl flooring. Each cycle began with a heel strike and terminated with the next heel strike. This information was used to synchronize the starting and ending of the gait cycles recorded by both the systems. The results from the vicon were filtered and the curves were smoothened with the in-built filters and were then time normalized to percentage of gait cycle and compared with the results from SUDALS. This is shown in **figure 3**.

3 RESULTS

The results of the bench-test indicate that there was an average standard deviation of 2° to 3.5° of the measurement range for all three electrogoniometers irrespective of the channels to which they are connected. The mean values demonstrated good linearity between the true input angles applied to the protractor and the measured output values recorded in computer units as shown in figures 1a and 1b. The averaged equation of the line of best fit for channel 1 was $Y = (-0.1536 * X + 314.95)$ and for channel 2 the equation was $Y = (-0.1570*X + 313.55)$, indicating that 0.15° was equivalent to one computer unit and that at 0° the computer would obtain a reading of 314 computer units. The mean absolute error for all the electrogoniometers was between 3° and maximum of 5°. This means that the system is able to quantify angular displacement to the nearest 0.15° with a 95% confidence interval of ± 6°. The results of the repeated trial were similar to those obtained from trial1, indicating that there was no variation in the calculated slope of the line (0.15° generated per computer unit). However, small variations (+ 0.3% and -0.4%) were found in the intercept of the line (314.9 - 316 computer units for channel1 and 313.5 - 312 computer units for channel 2) with the mean absolute error similar to those obtained in trial 1. Further, examination of figures 1a and 1b indicates the presence of a very small hysteretic effect and this is particularly noticeable around zero degrees where the curve appears to 'open up' slightly. In addition to this on analysing the results for differences ***between the electrogoniometers*** calibrated on two different occasions on the same day, variation among the coefficients of the electrogoniometers was 0.003 degree per computer unit for channel 1 and 0.001 degree per computer unit for channel 2, representing an error of 2° for channel 1 and an error of 0.6° for channel 2 when measuring 100°. On the other hand on analysing the results for differences ***within the electrogoniometers*** calibrated on two different occasions on the same day, little variation in the calibration coefficients was observed. For channel 1, the coefficients of electrogoniometer 2 varied from 0.151 to 0.154 and the coefficients of other two electrogoniometers remained the same. However, for channel 2, there were variations in the coefficients of electrogoniometer 1 (from 0.153 to 0.156) and 2 (from 0.152 to 0.157) and the coefficients of the third electrogoniometer remained the same. The variation in the slopes of the electrogoniometers will be introducing systematic errors varying from 2° to 3° over a measurement range of 100°.

Table 1 shows the mean maximum left and right knee joint angle for the group of 10 normal healthy young subjects during various ADL such as; gait, up and down the stairs, in and out of a chair and squat. **Table 2** shows the average knee joint excursion of the group for the left and right knees. The maximum knee joint excursion exhibited by the group was during squatting - 114°. During the other activities such as gait, up and down the stairs, their knee excursion was 66.2°, 71.5° and 65.6° respectively. Similarly, during getting in and out of the chair, the subjects seem to have to used a slightly high knee range of motion of 101° and 105°. On the other hand, on analysing the average maximum flexion angles of both the knees during the 6 ADL, the results seem to lie within the values published in the literature. Further, a Pearson correlation coefficient of 0.9 shows that, there is a high degree of correlation between the data recorded from all the three different trials, reflecting on the repeatability and reproducibility of the system. Figure 3 shows the comparison between the mean knee angle trace recorded via SUDALS and vicon system. There seems to be a good agreement between both the systems in terms of the knee joint excursion and maximum knee flexion angle. The excursion of the right knee of the group, recorded by SUDALS and vicon during gait was 63° and 58°. In addition to this, on analyzing the maximum flexion angle of the right knee of the group, recorded by SUDALS and vicon during gait showed 63° and 64° respectively. The above results show a good similarity between the data collected by both the systems.

4 Discussion

Over the last decade, flexible electrogoniometers have been used with commercially available data collecting systems by various researchers for numerous applications and vital properties of the electrogoniometers have been studied and reported by Rowe et al. [1]. However, none of these data acquisition systems facilitate remote control operation and wireless transmission of data. The dynamic ability of the system to record, store and transmit the data facilitates data collection in a non – laboratory setting and also enables the researcher or clinician to check whether the recorded data is reliable or not. The main aim of our study was to test the behaviour of these body mounted transducers when used with SUDALS. As mentioned above, during the bench tests, the electrogoniometers were manipulated through a range of angular displacements using a plastic protractor. However, literature reports the accuracy of such protractors to be less than a degree. On the other hand, research also reveals the existence of a slight non-linearity in the Poisson's ratio of the material used for designing the central shim of the electrogoniometer. As a result, for functional activities involving a joint movement of less than or equal to100°, one can expect a hysteretic effect of 1°. Though, the occurrence of systematic errors with the use of different electrogoniometers is not known, literature suggests that these variations between and within the electrogoniometers at different days or different times may be due to certain manufacture differences. [1]. Further, the absolute errors shown by the system may be due to these defects within the electrogoniometer. Regardless of such minor variations, research reveals the use of electrogoniometer in a variety of hospital settings, as it is not affected by environmental pollutants such as heat, electrical interference, convection currents or noise [1]. Although, our bench-tests indicated maximum absolute errors up to 5°, the r^2 value for the line of best fit for the all electrogoniometers was > 0.99 indicating a highly significant and linear correlation between the input and output. As mentioned earlier, the attachment procedures adopted here in this study is similar to those reported by Rowe et al. [1] Use of plastic strips, double sided tapes and Velcro straps have taken into account the errors due to skin movement, which otherwise could be up to 20°. Though, we haven't used foam blocks to compensate for errors due to abduction and adduction, the results of our study seems to be unaffected by such errors. The maximum knee flexion recorded by SUDALS during gait was 64°. This is close to those values reported by Jevsevar.D.S et al – 63.3° ± 8.1° and Kettlekamp et al – 67.4° [4 - 5]. In addition to gait, Jevsevar.D.S et al has also reported about the maximum knee flexion angle in young normal individuals during other ADL such as stair ascending / descending and getting out of a chair to be 91.8°±10.4° / 86.1°±5.5° and 90.05°±8.9°, which are very close to (86° / 80° and 108°) those recorded by SUDALS. Costigan et al has reported the maximum knee flexion during stair climbing to be 90°, whereas Protopapadaki et al has reported the maximum knee flexion to be 93.92°± 7.40° for stair climbing and 90.52°± 7.11° for getting in a chair [6 - 7]. Other than Wyss.U et al none of these authors have studied the movement of the knee during squatting. [8]. However, the maximum knee flexion (152°) reported by Wyss.U et al during squatting doesn't seem to be close to the value recorded by SUDALS. 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, where the subjects have performed a complete squat. Other than this, the remaining values seem to be very close to those published by other researchers with little variations. The reason for these variations could be that, none of these researchers have used flexible electrogoniometer for measuring the knee angle. Further, none of them have reported the excursion of the knee during these ADL. Thus, the above results show that SUDALS has the ability to measure knee movements accurately and reliably during ADL. As far as the reproducibility and repeatability of the SUDALS is concerned, Pearson correlation test was carried out between the data obtained from all the three trials. A correlation coefficient of; 0.94 between trial 1&2, 0.99 between trial 2&3 and 0.91 between trial 1&3 shows that there is a good correlation between each trial and results are reproducible. Also, the results of the validity studies, shows that there is a good concurrent validity among both the systems. A cross-correlation coefficient of 0.97 shows good synchronization between the systems and there are no differences or time lags between the systems. Though, there is a difference of 5° between the knee excursion values obtained from both the systems, the pattern of the trace obtained from both the systems are identical and the maximum knee flexion angles obtained from both the systems are similar with differences of only 1°. Such small variations have been reported previously by Rowe et al. [1]. The results of this validation study are with respect to the right knee only, as we were unable to collect data from the left knee due to certain technical issues that were present with the vicon system during the data collection. However, results of our pilot study shows good similarities between both the knees during ADL, which are similar to those reported in the literature.

5 Conclusion

In summary, the user friendly system of flexible electrogoniometer (SUDALS) seems to be a reliable method for collecting data from the knee during ADL. Further, compared to the conventional motion analysis systems such as Vicon system and other commercial hard wired systems; it offers increased mobility of the subjects produced by eliminating the inconvenience caused by long trailing cables. This in turn has facilitated data collection in an unconstrained and daily living environment. 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 and meaningful clinical data to the health care professionals regarding the dynamic behavior of the knee during functional activities.

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Figure captions:

Figure 1a – This is a calibration graph obtained using regression analysis, illustrating the variation of the recorded output in computer units (Y) with respect to variation in the input angle in terms of degrees (X).

Figure 1b – This is a calibration graph obtained using regression analysis, illustrating the conversion of computer units to angles. Here the X axis represents the computer units and the Y axis represents the output angles in degrees corresponding to each computer unit.

Figure 2a – This graph illustrates the flexion of the right knee of the group of 10 people when performing the activity of getting into a chair from the standing position. The plot is time normalised and are represented in terms of % gait cycle along the X axis and the Y axis represents the knee angles in degrees. Further, the graph also shows the knee flexion angles for ± 1 standard deviation of the group from the mean value. The maximum knee flexion noticed in this graph is as same as the value reported in table 2.

Figure 2b – This graph illustrates the flexion of the right knee of a single subject during all the three repeat sessions. The Pearson correlation coefficient of all the three trials shows that the data obtained from SUDALS is repeatable. The values are time normalized and are represented in terms of % gait cycle along the X axis and the Y axis represents the knee angles in degrees.

Figure 3 – This graph illustrates the similarity and concurrent validity between the data simultaneously collected from SUDALS and Vicon system during walking from the right knee of three normal subjects. The values from both the systems are time normalized and are represented in terms of % gait cycle along the X axis and the Y axis represents the knee angles in degrees.

Table Captions:

Table 1 – This table shows the maximum flexion angles pertaining to both the left and right knees from all the 10 normal subjects during walking, stair ascend and descend, in and out of chair and during deep squatting using 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 2 – This table shows the maximum knee excursion (difference between the maximum knee flexion and minimum knee flexion) angles pertaining to both the left and right knees from all the 10 normal subjects during walking, stair ascend and descend, in and out of chair and during deep squatting using 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°