

DEVELOPMENT OF THE FEEDBACK CONTROLLED INDENTATION SYSTEM FOR ASSESSING RISK OF PRESSURE ULCERS

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ABSTRACT

Pressure ulcers are a common secondary complication in people with disabilities. With the increasing number of people suffering from pressure ulcers, it is urgent to develop efficient research methods and devices in order to understand etiological causes of such disease for developing proper prevention and treatment strategies. In this study, we introduce an efficient and robust indenter system with the purpose of performing reliable indentation tests for the study of mechanical etiology of pressure ulcers.

BACKGROUND

Pressure ulcers are a common secondary complication in persons with spinal cord injury (SCI). People with SCI typically spend more than 12 hours on sitting each day with a diminished ability to relieve pressure on the load bearing soft tissues (Wang, 2001). Prolonged sitting without changing body position causes unusual concentrated pressure to the soft tissues of the buttock could lead to ischemia and pressure ulcers on buttock. In order to design specific strategies of preventing these pressure ulcers, we need to characterize the biomechanical properties of soft tissues. One of the most popular techniques for determining the *in vivo* biomechanical behaviors of soft tissues is the indentation test (Jan and Brienza, 2009; Jan et al, 2013). To obtain accurate results, a robust and reliable indentation test system is needed. The existing indenters are mainly manually controlled, and often yield corrupted experiment data because of patients' unexpected movements. To design an improved indenter, Proportional-Integral-Derivative (PID) control is introduced into the system. LabVIEW is used as a controller program that is capable of implementing PID control algorithm to perform indentation based on different experimental protocols, which has fast responses and is able to compensate research participants' movements.

HARDWARE DESIGN

One of the problems researchers faced in experiments using the state-of-the-art indenter systems (Jan and Brienza,

2009; Jan et al, 2013) is that during a relatively long test time (such as skin blood flow test), test participants may intentionally or unintentionally move. Without compensation for these movements, the indenter may not apply correct force (or pressure) to the test participants and even more, it could fail to contact the test participants' target body area. Therefore, the collected data were corrupted and must be discarded. The new design is to solve this problem and deliver more reliable experimental data. The indenter system consists of several main hardware components and some peripheral assistive devices, such as an ultrasound probe and a laser Doppler probe, which are connected on the tip of the indenter so as to acquire skin blood flow data and soft tissue deformation data for determining biomechanical properties of soft tissue. The system is controlled by LabVIEW Virtual Instrument program running on a personal computer, with a user friendly Graphical User Interface (GUI) control and data display panel. The hardware components include:

The Mechanical Frame

The mechanical frame holds the indenter. It (including the mechanical arms) has five degrees of freedom for adjusting position and angle. A cross positioner is used to help fine-adjust the position of load cell (Figure 1).

The Load Cell Sensor

The load cell sensor (UKS Series, LI-CHEN MEASURE, Kaohsiung, Taiwan) is used to acquire force data. It is capable of measuring maximum 20Kg force.

The Load Cell Sensor Amplifier

The load cell sensor amplifier (UEX-07, LI-CHEN MEASURE, Kaohsiung, Taiwan) amplifies and processes the faint signal from the load cell and displays the force data. It is capable of Analog-Digital (AD) conversion 120 times per second. The 0 – 20 mA electric data are sent via RS-232 port to the data acquisition device.

The Data Acquisition (DAQ) Device

The DAQ data acquisition device (USB-6218, National Instrument, Austin, TX, USA) takes in the analog signal at fast sampling rates with high accuracy. After ADC, the

signal is sent to computer via a USB port and is further processed by LabVIEW program.

The Linear Actuator

The linear actuator is responsible for performing indentation. The stepper motor is connected to a driver case that controls the precise movement of motor via RS-232 port. The driver case is connected to the computer via USB port and is controlled by the LabVIEW program. Serialized data are sent using Virtual Instrument Software Architecture (VISA) standard, which provides the programming interface between hardware components and developing environments such as LabVIEW to control the movement of linear actuator.

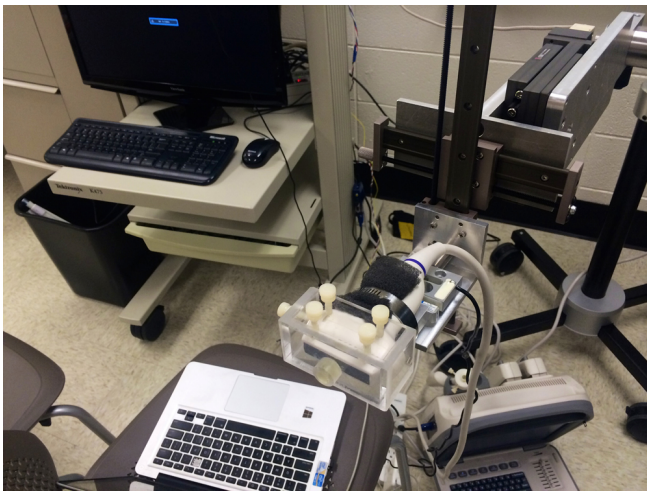


Figure 1. The indenter system paired with ultrasound probe.

SOFTWARE DESIGN AND ALGORITHMS

The PID Controller Implementation

Currently, the PID control method is the most widely used algorithm used in industry. To make a simple explanation, PID controller uses three terms in the feedback control: proportional (K_p), integral (K_i) and derivative (K_d). The proportional controller (K_p) will have the effect of reducing the rise time and will reduce but never eliminate the steady-state error. An integral control (K_i) will have the effect of eliminating the steady-state error, but it may make the transient response worse. A derivative control (K_d) will have the effect of increasing the stability of the system, reducing the overshoot, and improving the transient response (“PID Control”). The block diagram below (Figure 2) illustrates the algorithm described above.

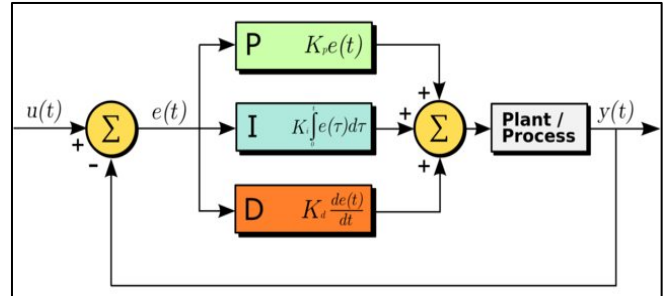


Figure 2. A block diagram of PID feedback controller (Liang, 2013)

In software design, we use National Instrument VISA (NI-VISA) library, to build a sub Virtual Instruments (VI) to communicate with the linear actuator (stepper motor) driver. The input value is simply decimals denoting the movement of stepper motor. Thus the output of PID controller is ready to accept by the driver without much modification (Figure 3).

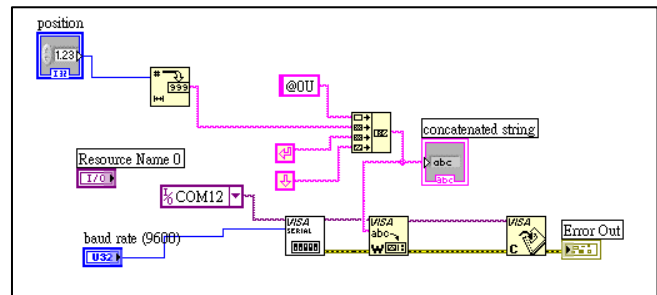


Figure 3. Stepper Motor Communication Sub VI.

To implement PID control, we make use of several PID Control VIs provided by National Instrument (Figure 4). The PID control with auto-tuning VI implements the standard PID control algorithm as the following equation,

$$u(t) = K_c[(SP - PV) + \frac{1}{T_i} \int_0^t (SP - PV) dt - T_d \frac{dPV_f}{dt}]$$

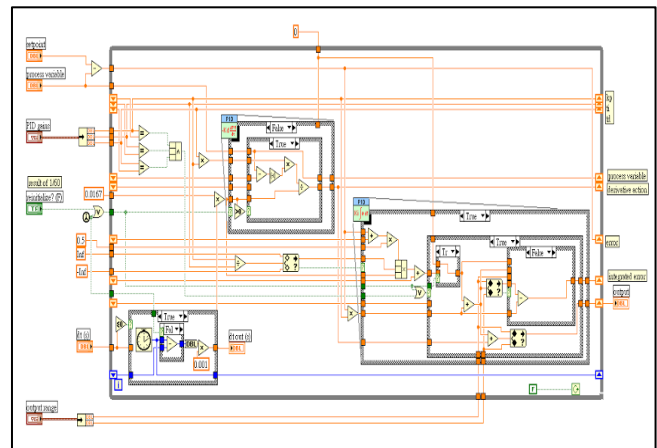


Figure 4. PID control VI implementation.

The block diagram of the program (LabVIEW source code) and the data display panel are shown in Figure 5 and Figure 6, respectively.

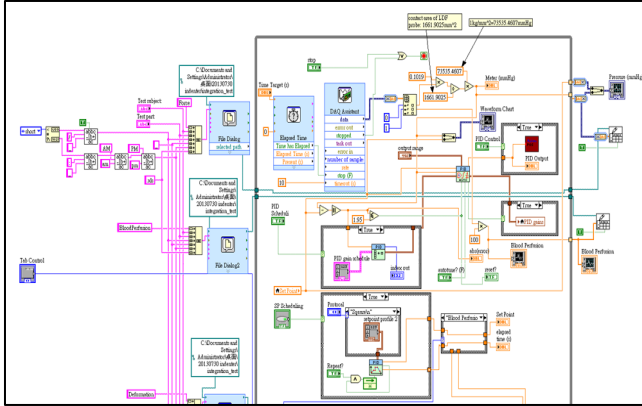


Figure 5. LabVIEW code for implementing PID control, data acquisition and file logging etc.

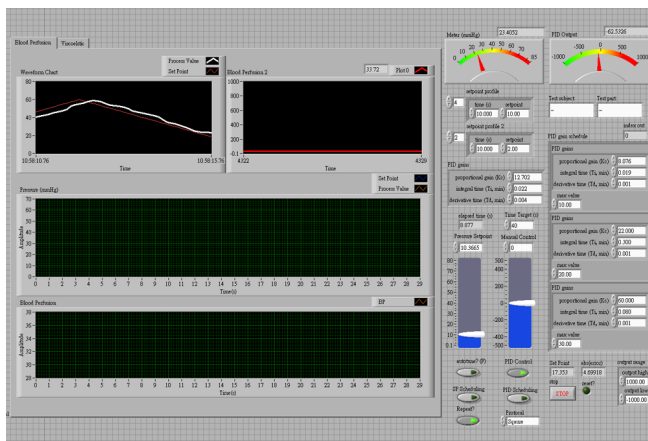


Figure 6. Front panel (user interface) of the program.

Where u is the output to be sent to the actuator driver; K_c , T_i (integral time), T_d (derivative time) are PID parameters, SP is the set point and PV is process value, which is the force read from load cell in our case. To get an ideal performance, we need to tune the parameters and this would be illustrated as follows. The VI also provides auto-tuning functionality. Once we have established a stable controller, we can make use of an auto-tuning wizard to gain better parameters.

However, during the experiment, the auto tuning functionality does not always generate satisfactory parameters that meet our requirement, and may sometimes even cause the system to become unstable. For example, in experiments we observe that the parameter set it gives works stably when the set point is within some ranges such as 0 – 25 mmHg, but in other ranges or some specific values such as 30 or 50mmHg the system swings back and forth

around set point value regularly (in some cases irregularly). Thus although we can use the auto-tuning wizard as a reference when improving the system, we would rely more on tuning the controller manually, which will be discussed later.

To improve the system, another technique known as gain scheduling based on the “state” of the system is introduced into the indenter system. An example is using different gain parameters once a certain set point has been reached, because the system responds differently once in steady-state (“Advanced Features in PID Tuning”). In our system, we define the state to be the difference between the set point and the process value (error). If the difference is small, we choose a conservative set of parameters to make the response smoother; else larger gains are used for faster response. In our case, when the error is less than 10mmHg, the system adapts $K_c=8.076$ $T_i=0.019$ $T_d=0.001$ and when the error is between 10mmHg and 20mmHg, $K_c=22$ $T_i=0.3$ $T_d=0.001$ is adapted, etc. The complete table (Table 1) and figure (Figure 7) is illustrated as follow.

Table 1. PID gain schedule parameters

Error	K_c	T_i	T_d
< 10mmHg	8.076	0.019	0.001
10 – 20 mmHg	22	0.3	0.001
20 – 30 mmHg	60	0.08	0
> 30 mmHg	86	0	0

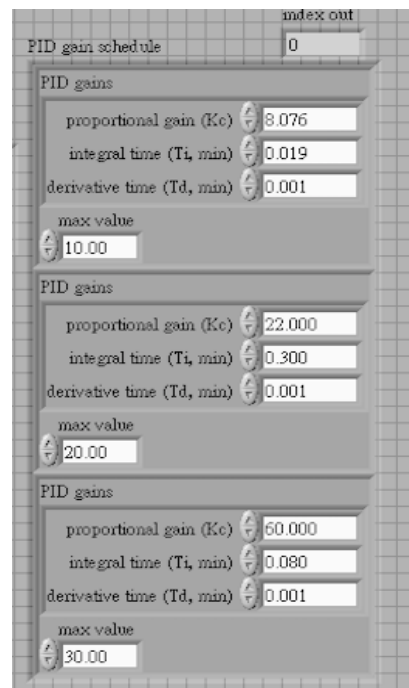


Figure 7. PID Parameter Schedule front panel.

TESTING OF THE SYSTEM

In order to test the functionality of the indentation system, we performed one primary application, which is measuring the blood perfusion change under indentation, because the experiment protocol allows us to see clearly how the indenter performs (compared to ultrasound elastography experiment). We attached a laser Doppler probe, which is 23mm in diameter, at the tip of the indenter to perform measurement. One participant, who is neurologically intact, was asked to lie in a prone position (Figure 10). The indenter was adjusted to point to the test participant's body perpendicularly in order to perform indentation tests on the lower back and sacrum, which is the most common site for pressure ulcers (Salzberg et al, 1996).



Figure 10. Indentation test on lower back.

Test protocol was applying ramping pressure from 10mmHg to 60mmHg in 120 seconds, holding the pressure at constant 60mmHg for 360 seconds, and then offloading the pressure to 10mmHg for 120seconds. The sampling rate of blood perfusion meter is set to 1/0.02s. Three of the measurements are illustrated below.

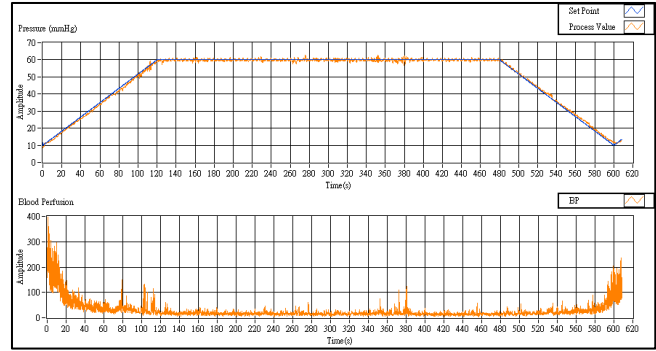


Figure 11. Blood perfusion data (up) and force data (down).

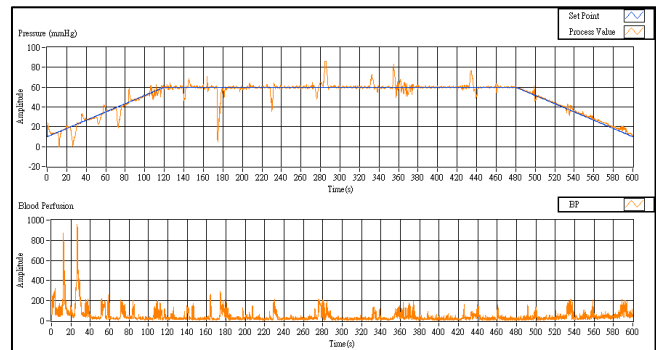


Figure 12. Test with intentional move.

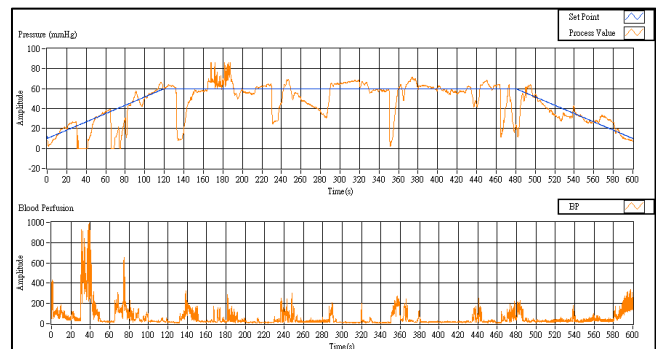


Figure 13. Test without feedback control.

In the first measurement, we asked the test participant to lie prone without any other intentional movements, so as to simulate the real test situation. We noticed that the participant might still move slightly and involuntarily during the experiment because of the subliminal intention to adjust the position. We observed in Figure 11 that the system was very stable and responsive, applying the target pressure to the participant as expected. Also, there was very little steady-state error between the set point and the process value, which was seen commonly on system without feedback control.

In the second experiment, we applied the same test protocol to the participant. The test participant was asked to move intentionally during the test this time. The movements include contracting the abdomen so that the lower back

moves down, lowering the pressure; trying to roll to the left or to the right; trying to stretch up in order to increase the pressure. These movements essentially represent the situation that participants move vertically and horizontally. We found out in Figure 12 that with the intentional movements, there were fluctuations in the pressure applied, but these errors could be compensated responsively. The system was able to adjust itself to error state to correct state in a reasonably short time.

In the third control group experiment, we still asked the participant to move intentionally. Nevertheless this time we turned off the PID feedback control, for the purpose of observing the improvement of the feedback-controlled system. The system was controlled manually. In order to make the pressure go from low to high and high to low, constant output was set to the linear actuator during 0 – 120s and 480 – 600s. Also we manually adjusted the indenter once we found the error was too large. It is obvious that the system failed to deliver satisfactory performance, compared to test with feedback control. From Figure 13, we observed that not only it took much more time to compensate the participant's intentional movement, but also large steady-state errors presented oftentimes. Furthermore, the system without PID feedback control requires the researcher to take care of it at all times when the experiment is being conducted, which is a major drawback compared to the feedback controlled system.

From the above results we can observe that the feedback-controlled indenter is capable of delivering target forces and remaining stable. If the participant moves, the controller can make compensation accordingly, yielding reliable data.

CONCLUSION AND FUTURE WORK

Our results show that the newly developed feedback controlled indenter system is capable of solving the problems raised at the beginning of the paper. When dealing with test participants' unexpected movements the system responsively makes compensatory adjustment of the indenter head to perform reliable measurements. It is important to note that the system is still not fully capable to compensate delicate and high frequency movements such as the one caused by breathing. This is our future work. We also work on the development of a more portable embedded system which can be more easily configured and setup, so that more therapists and researchers can easily make use of this technology for providing better preventive interventions and treatments.

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