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Ultrasound monitoring of inter-knee distances during gait

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Abstract—**Knee osteoarthritis is an extremely common, debilitating disease associated with pain and loss of function. There is considerable interest in monitoring lower limb alignment due to its close association with joint overload leading to disease progression. The effects of gait modifications that can lower joint loading are of particular interest. Here we describe an ultrasound-based system for monitoring an important aspect of dynamic lower limb alignment, the inter-knee distance during walking. Monitoring this gait parameter should facilitate studies in reducing knee loading, a primary risk factor of knee osteoarthritis progression. The portable device is composed of an ultrasound sensor connected to an Intel iMote2 equipped with Bluetooth wireless capability. Static tests and calibration results show that the sensor possesses an effective beam envelope of 120 degrees, with maximum distance errors of 10% at the envelope edges. Dynamic walking trials reveal close correlation of inter-knee distance trends between that measured by an optical system (Optotrak Certus NDI) and the sensor device. The maximum average root mean square error was found to be 1.46cm. Future work will focus on improving the accuracy of the device.**

I. INTRODUCTION

Analysis of human movement is most often conducted either via complex, lab-based, multi-camera 'motion capture' systems (or other optical sensors), or by using simpler, sensor-based systems, generally with more limited capabilities. Many potential applications of human movement analysis do not require the complexity of the camera-based systems. Within the second category of 'wearable'sensors, accelerometers and gyroscopes have been the most commonly used, either alone or in combination with other sensors such as magnetometers. However, other sensing technologies have potential use for specific clinical or ergonomic applications, particularly where the most commonly used sensors have limitations.

In the context of knee osteoarthritis (OA), dynamic malalignment ('bow legs') of the lower limbs contributes to over-loading the medial (inner) compartment of the knee joint, where most osteoarthritis occurs. This leads to pain and loss of function. As there is no cure for OA, with surgical joint replacement the only the end-term option in severe disease, there is much interest is developing conservative interventions that could slow the progression of the disease. Amongst these, it has been suggested that 'medialization' of the knees during walking gait (i.e., moving them closer together) can help to re-balance joint forces more evenly across the joint [1]. Given the close association between joint over-loading and OA progression [2], such load reducing strategies would be expected to slow the disease.

However, before such suggestions can be investigated, simple sensing technologies are required that will facilitate the teaching of such gait modifications to patients and assess their compliance, i.e. a simple means to sense the minimum distance between the knees during gait. Direct sensing of inter-knee distance has not been used before in the context of gait modification for knee OA. However, it has been used to encourage a wider base of support (i.e., greater distance between the knees), for improving balance in post-stroke patients [3, 4]. In this case, a capacitive sensing technology was used, however these sensors are affected by the type of walking surfaces.

Recent sensor technologies have considerable difficulty measuring distances accurately, for example, accelerometers and gyroscopes are subject to cumulative integration drift errors [5]. Magnetometers are sensitive to distortion from ferrous materials present especially in gait laboratories [6]. The global positioning system (GPS) does not provide sufficient position resolution and is furthermore not viable indoors.

This paper investigates the use of an ultrasound sensor as an alternative method for measuring limb displacements in gait, particularly in measuring the minimum inter-knee distances during walking. Section II details the design of the device while section III describes the experimental methodology. The following sections present the experimental results followed by a discussion on the viability of the method.

II. DEVICE DESIGN

A. The Ultrasound Sensor

Ultrasonic waves are high frequency acoustic waves (>20kHz) generated by mechanical movement of a surface, e.g. piezoelectric transducer. They can be used to measure distances by measuring the time it takes for the *echo* of a transmitted pulse (*chirp*) to return to the receiver (Figure 1). This distance d, can be calculated as follows:

$$d = \frac{1}{2} vt \cos\left(\frac{\theta}{2}\right) \tag{1.1}$$

where v is the velocity of sound (340 ms^{-1} in air at ambient temperatures), t the time elapsed before the echo is

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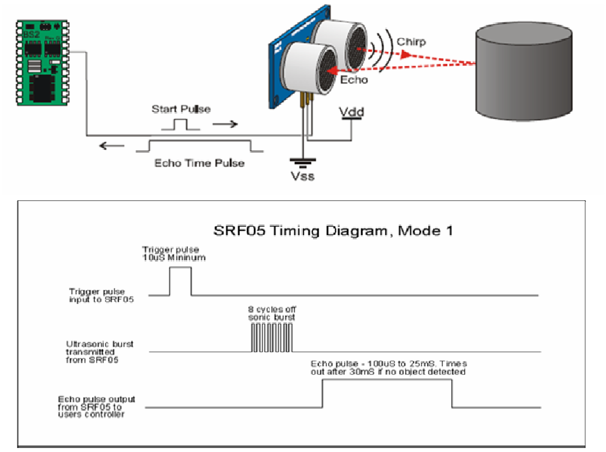

Figure 1: Operation and timing diagram for the Devantech SRF05 ultrasound sensor.

measured and θ the angle between the transmitter and receiver measured from an incident point. The input into the ultrasound is called the trigger pulse while the echo line indicates the measurement of a received echo. Ultrasound sensors have been popularly used in robotics navigation and sonar ranging and detection applications.

B. *Portable Device Design*

The portable monitor consists of an ultrasound transducer, Devantech SRF05 connected to an Intel iMote 2 sensor mote (Crossbow Technologies). The datasheet specified a minimal detection range of 3cm and a maximum range of 6m for the Devantech SRF05 with a maximum current draw of 4mA. These properties suited our application over other competing ultrasonic sensors, e.g. Maxbotix EZ1 and PING. The nominated maximum sampling rate was 20Hz with manufacturer suggestions that a 50ms delay between each pulse be added to allow time for the echo to subside.

The Intel iMote 2 has an onboard radio which is programmed to use the Zigbee protocol. However, we elected to use the Bluetooth protocol as it was still the dominant technology in portable devices such as mobile phones and PDAs. We used the Parani ESD 200 bluetooth solution which connected to the UART of the iMote 2 and allowed data to be transmitted using the serial protocol at 9600 baud.

C. *Principle of Operation*

When the ultrasound is triggered by the iMote 2, it sends a burst of ultrasonic waves at 40 KHz and sets its echo line high (Figure 1). The echo line is set low when an echo pulse is detected. The iMote 2 therefore monitors the echo line for a change in logic to determine the time for the return pulse. The distance is calculated on board and then transmitted via Bluetooth to a laptop base station. Signal trends are monitored and logged by a graphics user interface (GUI) programmed in Labview 8.0.

III. EXPERIMENTAL METHODOLOGY

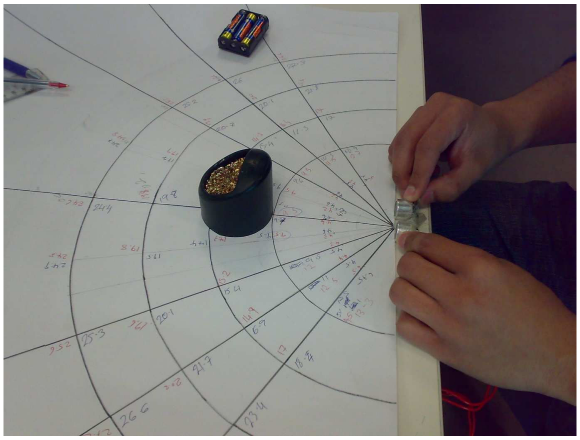

Figure 2: Beam angle chart for testing the ultrasound capabilities

A. *Experimental Setup for Static Tests*

The beam pattern of the sensor was tested by creating a beam angle chart (Figure 2) which was divided into major angles 60, 75, 90 (directly in front of the sensor), 105 and 120, degrees for distances of 5cm, 10cm, 15cm, 20cm and 25cm. Initially a circular object with a diameter of 10cm was placed on the chart at different distances and angles and the distance measured by the device recorded. A cylindrical object was selected to represent the curvature of the medial side of the knee.

Tests were conducted with the SRF05 placed horizontally on the table as in Figure 2 and vertically to investigate the two possible mounting positions on the inner knee. Multiple objects were also placed at different locations to record the sensor detection capabilities. It was quickly determined that in a multiple object scenario, the distance to the nearest object was returned and the horizontal position had fewer measurement errors.

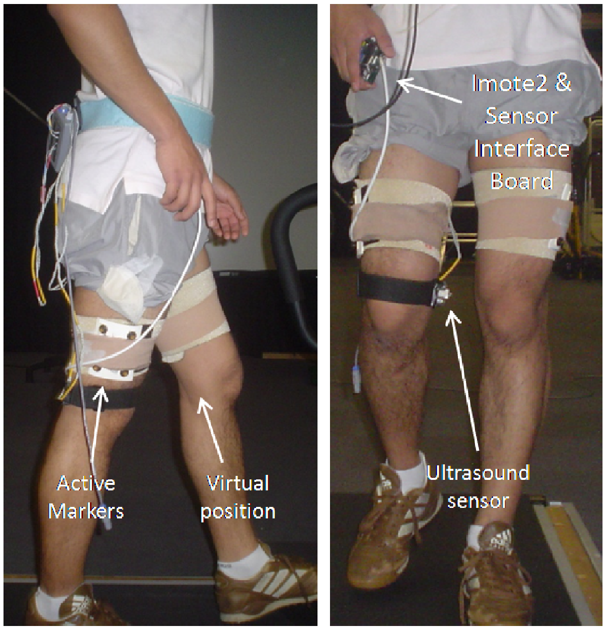

Figure 3: Experimental setup for treadmill walking with the portable device attached.

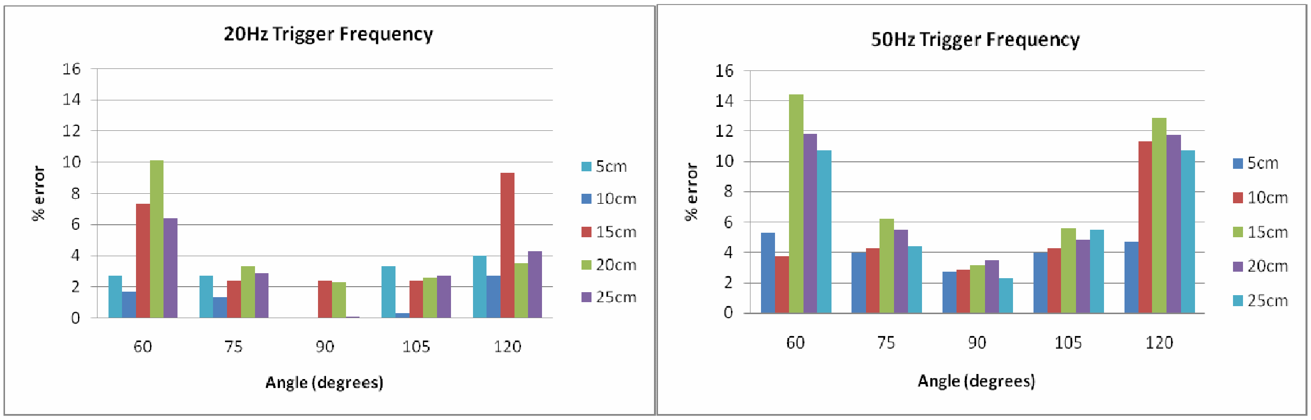

Figure 4: Histogram of average percentage errors for 20Hz and 50Hz triggering frequency. Input voltage is 3.9V.

A. *Static Tests*

In the static experiments, we tested the performance of the sensor under various operating parameters. The sensor was triggered at 20Hz (maximum recommended frequency) and 50Hz to investigate the differences in measurement error (Figure 4). The input voltage was varied between 5V to 3.9V and the static test repeated. Due to space constraints we only include results for 4.4V and 3.9V since 4.4V is the nominal operating voltage of the iMote 2 and 3.9V is the minimum voltage which permits Bluetooth transmission. For each experiment condition, the object was placed at the 25 positions randomly and the difference in actual distance and recorded distance from the ultrasound sensor was calculated. These were represented as percentage errors plotted in a histogram chart.

B. *Dynamic Experiments with Treadmill Walking*

The device performance was assessed in dynamic walking using the Optotrak Certus NDI video system at the Victoria University Biomechanics Lab. The ultrasound sensor was attached to the medial (inner) side of the right knee of one male subject, with its sensing direction oriented to the left. For Optotrak measurements the subject wore two rigid bodies positioned on the left and right thigh respectively (Figure 3). Each rigid body had 4 infrared active markers which were used to compute the position of a '*virtual point*' on the same-side thigh segment. One virtual point was placed on the ultrasound receiver and the other on the medial side of the left knee. The inter-knee distance measured by the Optotrak was the medial-lateral difference between these two virtual points.

The ultrasound sensor was triggered at 20Hz and the input voltage during data recording was only allowed to vary between 3.9-4.4V. A static measurement (subject standing straight with both legs aligned) was made with both the sensor and the Optotrak system showed close agreement (0.5cm averaged difference). The subject was then made to walk on a treadmill at speeds of 2,3,4 and 5km/h with three trials for each speed.

IV. EXPERIMENTAL RESULTS

A. *Static Test Results*

It can be seen from Figure 4 that the percentage of errors were considerably higher for objects placed at beam angles of 60 and 120 degrees for the 5 test distances. At 90 degrees, or when the object was directly ahead of the sensor, the percentage error was 0-2% while at the edges of the beam envelope, the errors were 2-10%. Detections of objects at further distances had higher errors in general, e.g. 6-10% for distances 15-25cm compared to 0-2% for 5-10cm. When the triggering frequency was increased to 50Hz, there was a noticeable increase in errors, e.g. 10-14% at the beam edges and 2-3% with objects directly ahead.

Figure 5 shows that the percentage errors did not vary significantly when the input voltage was altered from 3.3V-4.4V. At 4.4V the larger errors occurred near the edges of the beam envelope and the smaller errors from objects directly ahead of the sensor.

B. *Dynamic Test Results*

Figure 6 depicts a sample comparison between the inter-knee distances measured by the Optotrak and the ultrasound sensor for a trial at walking speed 2km/h. It can be seen that the inter-knee distances measured by the ultrasound follow the trend of the Optotrak virtual marker but are slightly out of phase. The minimum inter-knee distances are marked on the graph.

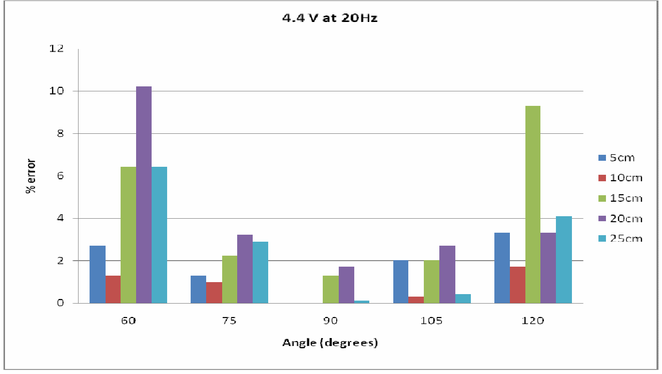

Figure 5: Comparison of average percentage errors for 20Hz triggering frequency for input voltages of 3.9V and 4.4V.

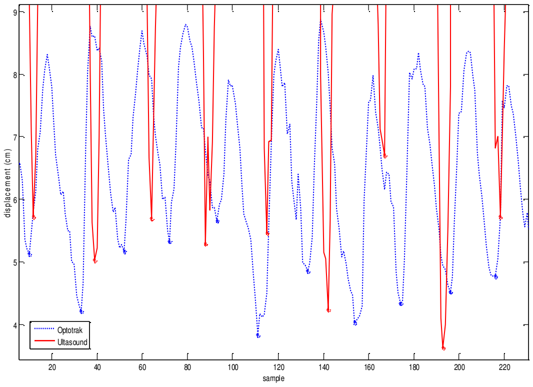

Figure 6: Sample comparison of minimum inter-knee distance between Optotrak and wireless ultrasound device. Walking speed is 2km/h on a treadmill.

TABLE 1: ROOT MEAN SQUARE ERROR (CM) OF MINIMUM INTER-KNEE DISPLACEMENT BETWEEN OPTOTRAK AND WIRELESS DEVICE

V(km/h)	Trial 1	Trial 2	Trial 3	Average
2	1.765	1.332	1.048	1.382
3	1.268	1.211	1.187	1.222
4	1.517	1.161	1.360	1.346
5	1.458	1.560	1.354	1.457

Table 1 shows the root mean square errors (RMSE) (cm) of the minimum inter-knee distances between the Optotrak and the ultrasound measurements. The average RMSEs were in the range of 1.2-1.5cm. Walking at 3km/h produced the lowest RMSE across the three trials, while the 5km/h walking trial had the largest average RMSE value of 1.457cm. There did not appear to be a distinct linear relationship between walking speeds and RMSE values.

V. DISCUSSION

We have designed a prototype for measuring inter-knee distances using an ultrasound sensor. While several 3D human motion capture systems have previously been based on ultrasonic technology, these are more complex than necessary for the current application (as are camera-based systems), and they require a fixed base station of receivers for triangulation of echoes to determine 3D location within a relatively small, fixed capture volume e.g. [7].

Initial calibration tests reveal the ultrasound sensor to be fairly accurate with maximum errors of 2-3% for objects directly opposite it. However in dynamic walking trials a larger than expected error was observed together with a variable phase delay when compared to the Optotrak motion capture system. These discrepancies could result from several issues. Firstly, comparisons were made between Optotrak virtual markers where an important assumption is that the rigid bodies must be rigidly fixed to the thigh segment. This is rarely achievable due to the unavoidable movement of underlying adipose tissue and muscle. Therefore, it is conceivable that the static tests represent a better indication of the sensor's inherent accuracy. Secondly our device did not monitor data throughput, raising the possibility that some sampled points may not have been successfully transmitted. This could explain the differences in synchronization of the two data streams and hence the appearance of phase lagging (Figure 6) between ultrasound and Optotrak measurements. In addition, dynamic gait activity results in additional issues such as Doppler effects, multipath echoes and multiple moving objects which were not accounted for in the static tests. The current device monitors inter-knee distances within a scope of 120 degrees of the sensor position, which means that it can only monitor a limited part of the gait cycle. This suited our application purposes since we were interested in only the minimum inter-knee distances. Future work is required to investigate multiple ultrasound sensors to increase the useable detection scope as well as the accuracy of detection.

VI. CONCLUSION

We have designed and tested a portable device for monitoring lower limb alignment, in particular the minimum inter-knee distances during walking. The device provided similar walking trends with RMSE values of 1.2-1.5cm when compared to a camera based video system. Future work will focus on techniques for reducing the errors in ultrasound sensor measurements. The device will be useful for monitoring walking strategies in patients with knee osteoarthritis and can be used in conjunction with biofeedback measures to improve rehabilitation programs.

VII. ACKNOWLEDGEMENT

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VIII. REFERENCES

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