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Paper:

An Ultrasound Technique of Bone Thickness Estimation for Pedicle Screw Insertion

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Information on bone thickness is useful to surgeons in fixing pedicle screws in place. The quality of pedicle screw insertion continues to increase with the introduction of such techniques as navigation based on computed tomography and fluoroscopy. These techniques reduce error in pedicle screw placement and injury. However, the information reported on the real time measurement of depths drilled through cancellous bone, also known as trabecular bone or sponge bone, by the pedicle screw is minimal. It currently depends on palpation by the physician for judging the boundary between cortical and cancellous bone – an inaccurate technique that may produce errors in screw placement and the risk of injury during surgical processes. Ultrasound is used to help overcome such problems. Bone thickness is estimated in this study using an ultrasound transducer attached to 20 mm of polymethyl methacrylate, a clear glass-like acrylic. The bone thickness of five specimens was measured using ultrasound echo signals. Error in estimating bone thickness was small, 8.121%, showing the accuracy in bone thickness to be more than 90.00% which is suitable for use in estimating bone thickness in pedicle screw insertion.

Keywords: pedicle screw, ultrasound transducer, pulse-echo technique, cancellous bone, bone thickness

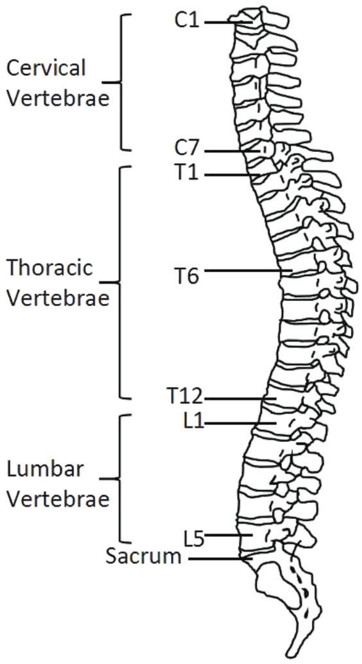


Fig. 1. Structure of human vertebrae.

1. Introduction

The human spine has 24 vertebrae, coded by number. The spinal lumbar region is between the thoracic regions and the sacrum as shown in **Fig. 1**. Pedicles, as the strongest part of the vertebrae, maintain the bone-metal junction if large force is applied to the spine. Each side of a vertebra has its own pedicle. The human body has two types of bone – spongy or cancellous bone, which has a higher surface-area-to-mass ratio because it is less dense, and cortical bone, which is the outer layer and, as the hardest part of bone, covers cancellous bone. Both cancellous and cortical bone are also classified based on volume fraction.

Cancellous bone, classified as trabecular, has less than 70% while cortical bone has a volume fraction of more than 70% [1].

1.1. Ultrasonic Backscattered Measurement

An ultrasound wave has a center frequency of more than 20 kHz. With its uses increasing annually in number, ultrasound and has been used for decades in many applications – in civil engineering to detect cracks in beams, on ships to measure ocean depth and in medical areas such as diagnostics. The ultrasound-based diagnostic sonographic scanner operates in a frequency range of 2–18 MHz [2] and is mostly used in cardiology to diagnose dilation of the heart and to estimate fetal cranial volume.

In this study, the ultrasound transducer transmits pulses and propagates them to cancellous bone. When the signal contacts the bone surface, the backscattered echo is picked up by the transducer receiver – called pulse echo and used in medical applications for decades [3]. Pulse echo provides a new way to assess bone features. In the clinical setting, transverse and axial transmission is generally used at peripheral skeletal sites such as the forearm and heel. In contrast, pulse echo may ease access to skeletal sites such as the hip and spine.

1.2. Pedicle Screw

The pedicle screw has been used since the 1940s [4] and was originally designed to stabilize spinal bone. The pedicle screw has several advantages over other methods such as greater pullout strength [5], more sagittal control, and, with three-column fixation, the most rigid construct [6, 7].

The pedicle screw usually provides greater rigidity with an improved fusion rate, and was designed to be implanted in vertebral pedicle bone. Although originally used for fixing the spine in place, the pedicle screw has several limitations [8, 9]. It is difficult to use in pediatric subjects because of their small spines, for example, and pedicle screw fixation is limited by structural variations in pedicle conformation [10–13]. Precision in pedicle screw placement depends greatly on the surgeon's skill and experience.

Error in pedicle screw placement is also high, and the screw may cause neural injury or cracks to the bone if it penetrates the pedicle cortex. In surgery, it also involves the risk of blood loss and a high infection rate.

1.3. Pedicle Screw Placement

Free-hand pedicle screw insertion, which has been used since 1940, is the technique with which most surgeons are familiar. The freehand technique, which requires surgical skill and experience to be successful. The technique has a screw misplacement and injury rate from 15% to 56%, depending on the surgeon's skill [14–18]. The accuracy of pedicle screw insertion has been increased using image-guided computed tomography, which has reduced the need for radiation during surgery [19–22]. Advances in navigation systems have broadened the use of the pedicle screw to the cervical spine and thorax, for example.

The automatic or robotic platform technique has also improved pedicle screw placement, reducing screw misplacement. It is costly, and requires a long learning curve, making it mostly unsuitable for small hospitals or clinics [23–25]. Despite being fully automated, pedicle screw placement in the spine is still performed using computed tomography for monitoring.

The template technique proposed by Sheng Lu et al. in 2012 was applied in scoliosis subjects [26]. This technique is easy to use and the surgeon can decide location, orientation and screw size before surgery. Pedicle screw insertion also avoids injury to the blood vessels and bone. One disadvantage of this technique is that the surgeon must remove muscle and fat attached to the bone, and cleaning requires that the surgeon be more careful during surgery not to damage the bone surface and ensure that the drill template fits properly on the lamina.

1.4. Bone Thickness Measurement

In 2011, Regine Wolff et al. described a new way to determine thin hard tissue structures [27] by using infrared light. They examined the possibility of measuring bone thickness by measuring light reflection. Specimens used in experiments were of bone tissues with different thicknesses. Light radiation was analyzed to obtain information on these specimens. The pixel was used to measure the light intensity of individual specimens.

Results showed that the receiver received low illumination, so average intensity increased with increasing bone thickness. All specimens tested gave the same pattern of results. However, they did not compare the average intensity for different specimens.

Other researchers used the ultrasound transducer to measure bone thickness. Janne et al. used two ultrasonic transducers and computed tomography scanner to measure cortical bone layer thickness [28]. Their objective was to determine the relationship between cortical bone and the ultrasound pulse echo using signal processing envelope and cepstral methods, from which results showed a high correlation ($r \geq 0.95$) between the thickness obtained using digital calipers and signal processing. However, It is difficult to place two transducers on opposite sides of a bone to determine cortical bone thickness in the spine during surgery. Hakim et. al measured cranial bone thickness using A-mode ultrasound and compared results with measured using digital calipers [29].

In 2009, Tretbar et al. used the ultrasound transducer to measure skull bone thickness in experiments with different pulse characteristics measured in water with a 2.25 MHz ultrasound transducer directly attached to specimens [30] and using coded excitation to enhance the ultrasound back echo signal. The study by Tretbar et al. used 16 randomly selected specimens of human cadaveric skull bones and measured the average difference bone thickness using a SonoPointer and the value measured by digital calipers was 0.04 ± 0.62 mm.

Despite the many techniques reported in clinical studies, data in the literature on real-time bone thickness measurement remains insufficient. Most bone thickness measurement is based on a computed tomography scanner offline. Bone thicknesses were also measured using a pair of ultrasound transducers, i.e., a transmitter and receiver, which is not suitable in clinical applications due to the narrow space measured. Our study used only one transducer working as both the transmitter and receiver in measuring bone thickness. Furthermore, it important that the pedicle screw be inserted safely as determined by measuring bone thickness using an ultrasound sensor. This study employed the pulse-echo technique and focused on measuring cancellous bone thickness and corroborating ultrasound versus caliper measurements. The detection system

Fig. 2. Specimens for measurement divided into different parts based on specimen size.

was developed using a C++ builder and through this system, the signal will be analyzed for signal peak detection and time interval determination.

2. Methodology

2.1. Specimens Preparation

The study described here examined the possibility of measuring bone thickness using back echo reflection alone from the ultrasound transducer. Five porcine specimens bone of different thicknesses were used to verify this hypothesis experimentally. Individual specimens were each divided into different areas or parts to measure bone thickness. A different area from each specimen was divided based on bone size as shown in **Fig. 2**, yielding 12 individual bone areas measured. The Echo backscatter amplitude was measured at the center of each specified area and each area was measured five times to examine measurement values. Before experiments were run, all specimens were degassed in water for 24 hours to improve the propagation rate of ultrasound signals through specimens. Boiling was used to remove all soft tissue such as blood, fat and muscles.

2.2. Signal Processing

The signal produced by the ultrasound transducer was analyzed to determine time interval Δt between the transducer and the echo backscatter area [30–32]. The detection system was developed using a C++ builder and through this system, the signal is analyzed for detecting signal peaks and determining time intervals as shown in **Fig. 3**. Basic algorithms used are as follows,

$$(Data[i] - Data[i-1] > 0.2) \quad \ldots\ldots \quad (1)$$

$$(Data[i+1] - Data[i] < 0.1) \quad \ldots\ldots \quad (2)$$

where $Data[i]$ is a data sample that starts from $i = 1$ to total number of data, $i = n$. The threshold value was set to 0.2 V for the inclining peak and to 0.1 V for the declining peak. When condition for both equations are fulfilled, the travel time value is determined.

Bone thickness measurement is detailed in **Fig. 4**. The thickness of individual specimens was measured at the same position. All measurements were at room temperature, i.e., 25°C. The variable of "a1" in **Fig. 4** shows that the area of the first echo that appears refers to a plastic echo and "a2" refers to a bone echo. Time interval be-

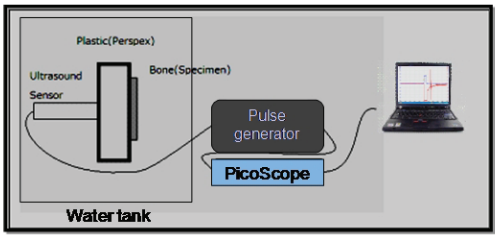


Fig. 3. Experimental setup for measuring bone thickness.

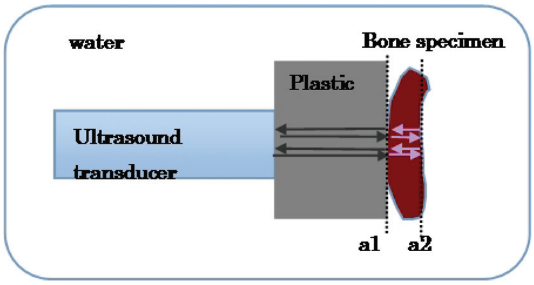


Fig. 4. Bone thickness measurement details.

tween the transducer and plastic, $t(u\&p)$ was measured based on pulse travels flight times from the transducer to a1 and return to the transducer. In addition to the time interval between the transducer and bone, $t(u\&(p+b))$ was measured based on pulse travel flight times from the transducer to a2 and return to the transducer. In-bone time interval only Δtb is calculated using Eq. (3), then Δtb was used to estimate bone thickness. Sound velocity c in the material must be known because different materials have different sound velocities. Eq. (4) was therefore used to estimate bone thickness [33],

$$\Delta tb = t(u\&(p+b)) - t(u\&b) \quad \ldots\ldots \quad (3)$$

$$d = \frac{c\Delta tb}{2} \quad \ldots\ldots \quad (4)$$

where c is specimen sound velocity in meters per second and d is specimen thickness in meters.

In experiments, an ultrasound transducer 10 mm in diameter and plastic (acrylic) were used to estimate bone thickness. Plastic 20 mm thick was attached to the bone surface to produce a time delay before the bone pulse echo appeared. Specimens were from 1 mm to 3 mm thick. All of this was done because if the ultrasound transducer were attached directly to the bone surface, the time in-

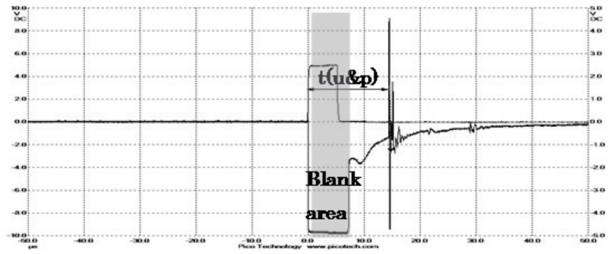


Fig. 5. Ultrasound signal analysis.

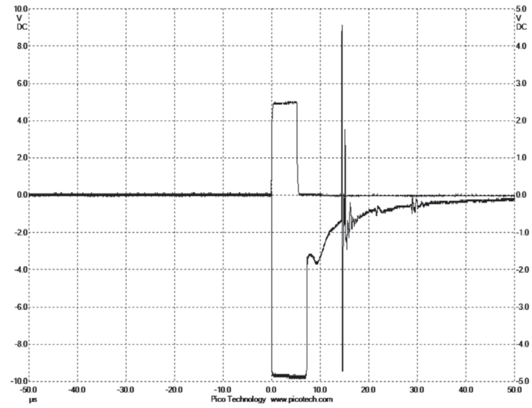
terval between the transducer and the bone could not be measured because the back echo starting point would appear in a blank area, as shown in **Fig. 5**. Using plastic to form a gap between the transducer and bone shifted the starting point to a positive area where the time interval between the pulse transducer and plastic, the $t(u\&p)$ pulse transducer and bone $t(u\&(p+b))$ were easy to determine. **Fig. 5** shows a sample echo received in experiments.

Ultrasound wave velocity in the material is important for calculating distance beforehand. Ultrasound wave velocity in plastic was 2760 m/s and cancellous bone used in experiments was 1566 m/s. In 1997, Hosokawa and Otani reported ultrasound wave propagation in bovine cancellous bone [1], i.e., 1450 m/s propagation velocity. Jin Ho Chang et al. used 1500 m/s ultrasound wave velocity in cancellous bone to measure ultrasound response in ovine vertebral bodies [34]. Mujagic et al. also used the same ultrasound wave velocity in cancellous bone, i.e., 1500 m/s [35]. In the study reported in this paper, we used 1566 m/s ultrasound velocity based on the results of our experiments.

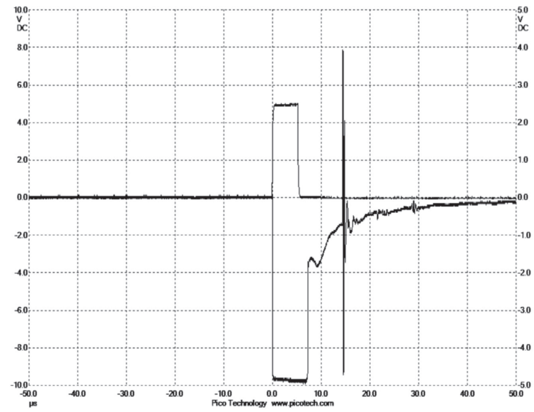
2.3. Experimental Setup

Our study used a transducer, a pulse generator/receiver and an AD converter. The ultrasound transducer center frequency was 2.5 MHz and the transducer was 10 mm in diameter. The transducer was used in experiments as a transceiver. Bone thickness was estimated using a standard approach involving a pulse echo in a water tank. A pulse generator filtered out unwanted signals and amplified ultrasound signals. An AD converter (PicoScope 3205A series PC oscilloscopes, Pico Technology) was used as an oscilloscope to display signals received from the pulse generator/receiver. The AD converter was designed to perform a variety of applications such as spectrum analysis and a variety of mathematical calculations on input signals.

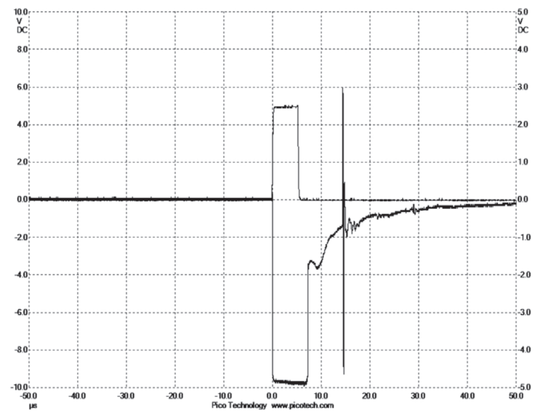
The experimental setup is shown in **Fig. 3**. Prior experiments were run, the thickness of all specimens was measured manually using highly precise vernier calipers, which the accuracy was 0.1 mm. Caliper values were used for comparing and validating experimental values because most researchers used calipers in their work [28–30].



(a) Ultrasound wave for Part A of specimen 1.



(b) Ultrasound wave for Part B of specimen 1.



(c) Ultrasound wave for Part C of specimen 1.

Fig. 6. Ultrasound wave results for specimen 1.

3. Results

The thickness of all specimens was measured using the ultrasound transducer. Calculated results were compared to manual readings using vernier calipers. As explained in the previous section, the experiments used plastic 20 mm thick to measure bone thickness. The time required for measuring each part of the specimens was measured five times. **Fig. 6** shows specimen 1 results for part A. The average signal travel flight time in bone for part A was

Table 1. Flight time of signal travel in bone, Δtb and comparison of bone thickness using vernier calipers and the pulse-echo technique.

Specimen	Flight Time of Signal Travels In Bone, Δtb, us						Average, us	Bone Thickness (Pulse-echo technique), mm						Average, mm	Bone Thickness (Vernier Calipers), mm	Error	
	1	2	3	4	5	STD		1	2	3	4	5	STD			mm	%
1 A	1.830	1.850	2.020	1.990	1.920	0.083	1.616	1.433	1.449	1.582	1.558	1.503	0.065	1.505	1.460	0.045	3.077
1 B	1.800	1.920	2.360	1.950	1.910	0.216	1.693	1.409	1.503	1.848	1.527	1.496	0.169	1.557	1.720	0.163	9.500
1 C	1.960	2.030	1.920	1.730	1.740	0.135	1.586	1.535	1.589	1.503	1.355	1.362	0.105	1.469	1.830	0.361	19.732
2 A	2.870	2.840	3.080	2.500	2.840	0.208	2.390	2.247	2.224	2.412	1.958	2.224	0.163	2.213	2.240	0.027	1.216
2 B	3.170	3.350	3.470	3.290	3.140	0.135	2.759	2.482	2.623	2.717	2.576	2.459	0.106	2.571	2.550	0.021	0.838
2 C	3.750	3.580	3.430	3.470	3.580	0.124	2.989	2.936	2.803	2.686	2.717	2.803	0.097	2.789	2.510	0.279	11.117
3 A	1.550	2.320	2.180	2.180	1.810	0.318	1.726	1.214	1.817	1.707	1.707	1.417	0.249	1.572	1.580	0.008	0.490
3 B	1.670	1.620	1.850	1.630	1.660	0.094	1.421	1.308	1.268	1.449	1.276	1.300	0.074	1.320	1.410	0.090	6.373
3 C	2.300	1.680	2.340	2.320	2.140	0.278	1.843	1.801	1.315	1.832	1.817	1.676	0.217	1.688	1.760	0.072	4.083
4 A	3.650	3.670	3.760	3.300	3.210	0.246	2.973	2.858	2.874	2.944	2.584	2.513	0.192	2.755	2.880	0.125	4.354
4 B	2.960	3.000	2.980	2.820	2.500	0.209	2.412	2.318	2.349	2.333	2.208	1.958	0.164	2.233	2.830	0.597	21.091
5 A	3.470	3.390	3.390	3.580	3.690	0.130	2.942	2.717	2.654	2.654	2.803	2.889	0.102	2.744	3.250	0.506	15.581
Average																0.191	8.121
Standard deviation (STD)																0.200	7.308

1.616 μs, for part B 1.693 μs and for part C 1.586 μs. The average bone thickness measured by the pulse echo for part A was 1.505 mm, 1.557 mm for part B and 1.469 mm for part C. The standard deviation was 0.065 mm for part A, 0.169 mm for part B and 0.105 mm for part C. **Table 1** shows the details results.

As shown in **Table 1**, bone thickness value determined using the pulse-echo technique were similar to reference values measured using vernier calipers, i.e., 1.460 mm for part A, 1.720 mm for part B and 1.830 mm for part C. The bone thickness error between pulse-echo and caliper values for specimen 1 was 3.077% for part A, 9.500% for part B and 19.732% for part C.

Specimen 2 was divided into three parts. Pulse travel flight time in specimen 2 averaged 2.390 μs for part A, 2.759 μs for part B and 2.989 μs for part C. Specimen 2 bone thickness was measured based on the time determined from when an echo appeared. The measurement of bone thickness using the pulse-echo technique was 2.213 mm for part A, 2.571 mm for part B and 2.789 mm for part C. The percentage difference between pulse-echo and caliper measurement value averaged 1.216% for part A, 0.838% for part B and 11.117% for part C. Specimen 3 pulse travel flight time averaged 1.726 μs for part A, 1.421 μs for part B and 1.843 μs for part C. The actual specimen 3 thickness measured using calipers was 1.580 mm for part A, 1.410 mm for part B and 1.760 mm for part C. Specimen 3 percentage error between pulse-echo and caliper measurement was 0.490% for part A, 6.373% for part B and 4.083% for part C.

Specimen 4 was divided into two parts, A and B. Thickness measured using vernier calipers was 2.880 mm for part A and 2.830 mm for part B. The percentage difference between pulse-echo and vernier caliper measurement was 4.354% for part A and 21.091% for part B. Specimen 5 flight time travel was 2.942 μs and bone thickness measured by the pulse-echo technique averaged 2.744 mm compared to 3.25 mm measured using vernier calipers. The percentage difference between the two measurements was 15.581%. The highest percentage difference in this study between the two measurements was 21.091% for specimen 4 part B and the lowest 0.838% for specimen 2 part B.

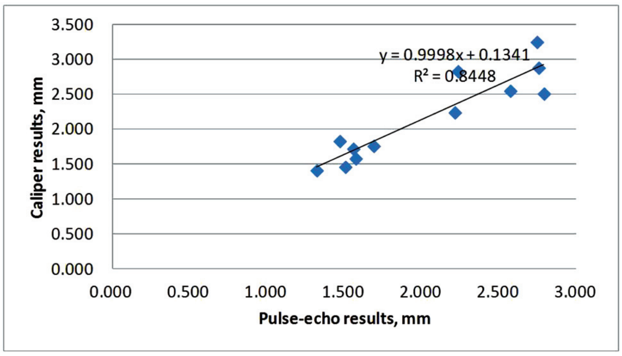


Fig. 7. Statistical results between calipers and pulse-echo technique.

Percentage differences were significantly lower for other specimens. The bone thickness percentage difference for all specimens averaged 8.121% and standard deviation was 0.200 mm, showing that the accuracy of the bone thickness measurement using an ultrasound transducer and 20 mm plastic was 91.879%. **Table 1** shows that the minimum specimen thickness of 1.460 mm, as measured using the pulse-echo technique, while the error was only 0.045 mm. Maximum thickness of 3.250 mm was measured using pulse-echo technique and error was 0.506 mm. Statistical analysis showed that results correlated well at $r = 0.9191$ between thicknesses obtained by the two methods, as shown in **Fig. 7**.

4. Discussion

The pedicle screw provides stability and rigid fixation in problems of the spine. Although its use in spinal fixation is increasing, however, the pedicle screw has limitations. Based on previous research, overall error rate ranged from 15% to 56% for the free-hand technique [18, 36]. With using free-hand technique, about 10% of cases cases were happened in intraoperative period such as nerve root injury, vascular injury, pedicle fracture, bleeding, insufficient screw positioning and screw penetration of the cortical bone. The risk of screw misplacement damaging the neurological pedestal rises higher the smaller the pedicle size, potentially adversely affecting the spinal cord, aorta, vena cava, etc [37, 38]. The range of thoracic pedicle wall violation was 15.9% to 54.7% [39, 40]. In 1995, Vaccaro et al. reported that 41% of 90 screws placed using the free-hand technique performed by five experienced surgeons penetrated the pedicle cortex. Liljenqvist et al., using 120 thoracic pedicle screws in subjects with idiopathic scoliosis, reported that 30 thoracic pedicle screws were improperly positioned [41].

Screw placement accuracy was improved using image-guided techniques, which reduced the screw fixation error rate between 10% to 53% [18]. C-arm fluroscophy, particle probes and serial radiology are used during the surgical process. Carbone et al. used this for placing 126 thoracic screws in 22 subjects having thoracic thoracolumbar injury. The penetration rate was 12.7%, which means that 16 screws penetrated the cortical area in these 22 subjects [42]. Although this technique made pedicle screw insertion more accurate, the percentage of screw misplacement was still high. Image-guided technique also has disadvantages such as high radiation exposure during use of the fluoroscopy machine [43] and long surgery time. Fluoroscopy machines also do not provide the axial plan view. This view is important to spinal fixation because it provides critical trajectory information.

Pedicle screw length and diameter are determined preoperatively using CT scanning, which is comparatively easy to use and whose imaging provides detailed information for pedicle screw placement. Pedicle screw positioning in the spine is also determined postoperatively using the CT scanner. Surgeons usually use pedicle probes to monitor drilled hole depth before inserting the pedicle screw. CT scanning is often used postoperatively by surgeons to determine the boundary between cancellous and cortical bone, and the gap between the pedicle screw and pedicle cortex. CT scanning provides bone thickness and pedicle screw dimension data, which were collected pre- and postoperatively. During surgery, most surgeons also use pedicle probes to determine the boundary between cancellous and cortical bone, although this is not accurate. Although many researchers have compared different pedicle screw insertion techniques [18, 44, 45], they did little to determine the boundary between cancellous and cortical bone in fixing pedicle screws.

This paper has demonstrated the use of a simple ultrasonic transducer based on the pulse-echo technique for measuring bone thickness. This proposal for using ultrasound measurement may thus provide more accurate estimations of bone thickness. The suitability of sound velocity has been reported for use in cancellous bone when measuring bone thickness. The study of ultrasound assessment for determining bone mineral has been reported elsewhere [31, 46], as has bone thickness measurement [47, 48].

Pulseecho mode has provided information useful in predicting bone thickness for the pedicle screw insertion [47, 48]. Sound velocity in cancellous and cortical bone was not constant because of the bone properties themselves. Sound velocity used in several studies has been found to be between 1400 m/s and 2000 m/s [1, 30]. In addition to sound velocity in cortical bone, small sound velocity variations occur from 3200 m/s to 3485 m/s [34], adversely affecting the accuracy of bone thickness measurement. The study detailed in our paper used cancellous bone layer sound velocity at 1566 m/s to measure bone thickness, finding a relatively small variation in bone thickness compared to manual measurement. This demonstrates the results of percentage differences between experimental and manual measurements of 90% for a standard deviation of 0.200 mm.

5. Conclusions

An ultrasound transducer applying the pulse-echo technique has been used to determine bone thickness. As shown in **Table 1**, bone thickness error averaged 0.191 mm (8.121%). Standard deviation in average error was 0.200 mm – smaller than that of previous methods by several researchers. This value has demonstrated that this accuracy is almost 90.00%. Results for our proposal also have correlated highly at $r = 0.9191$ between thickness obtained using vernier calipers and that obtained using the pulse-echo technique. In conclusion, this method has proven suitable for use in measuring bone thickness for pedicle screw insertion, although more research is needed.

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