The Accuracy of Ultrasonic Indentation in Detecting Simulated Bone Displacement: A Comparison of Three Techniques

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Abstract

Purpose: Palpation is used most commonly to assess tissue stiffness despite its well-known deficiencies. As an improvement, a mechanical technique known as ultrasonic indentation has been proposed. The purpose of this study was to compare the accuracy of 3 ultrasonic indentation techniques in quantifying bone displacement in a specially constructed tissue simulator.

Methods: Three ultrasonic indentation techniques were tested for their accuracy: a rigid, laboratory-based method (rigid), a less rigid system actuated by hand (assisted), and a totally free-hand system (handheld). Each indentation technique was applied on a tissue simulator, which consisted of a deformable phantom overlying a displaceable piston to simulate soft tissue overlying bone. Measures of piston (ie, bone) displacement obtained by each indentation technique were compared with a gold standard of piston displacement to determine the accuracy of each technique. Statistical tests were used to determine if differences between experimental and reference measures of piston displacement were significant.

Results: When indented, phantom deformation preceded piston displacement because of unequal stiffness between the two. The rigid and assisted indentation techniques showed the best accuracy for measuring simulated bone displacement. Differences in accuracy between the rigid and assisted techniques were insignificant. The accuracy of the handheld technique was significantly less than the rigid and assisted techniques.

Conclusions: The clinical utility of assisted ultrasonic indentation should be explored given its accuracy and the excessive size, cost, and complexity of the rigid technique. The large error magnitude of the handheld technique may exclude it from clinical use now. (J Manipulative Physiol Ther 2006;29:126-133)

Key Indexing Terms: *Palpation; Ultrasonography; Indentation; Accuracy*

Palpation is a clinical technique where an examiner's hands are placed on a patient to provide subjective information regarding the patient's state of injury or pathology. Because of the variety of sensory organs within the hands, palpation has been used historically to assess a wide range of human conditions that feature temperature change,[1] alterations in skin texture,[2] changes in heart rate,[3] or alterations in tissue stiffness. Tissue stiffness is defined as the resulting tissue displacement for an applied load. When that load is applied by hand, tissue stiffness is appreciated as the resistance of a tissue to compression. Manual assessment of tissue stiffness has been used to examine discrete regions (eg, tumors[4]), entire tissues (eg, glaucoma[5]), or in dynamic structures such as joints (eg, arthritis[6]).

Although used for millennia, investigations in the last century have shown that palpation is typically less accurate and reliable than other forms of assessment. Although some aspects of palpation can improve with training,[7,8] palpation has been shown to be problematic in the detection of cancer,[9-12] assessment of joint laxity,[13] determination of fetal position[14], glaucoma,[15] and in assessing circulatory disorders[3,16] As a specific form of palpation, manual assessment of tissue stiffness fares no better. Judgments made by experienced manipulative physical therapists were found to have poor reliability[17] and tended to underestimate the magnitude of applied force and overestimate tissue motion.[18] Although explanations for these deficiencies may be related to the magnitude of detection sensitivity[15,19] or multidimensional factors,[20,21] the limitations of manual

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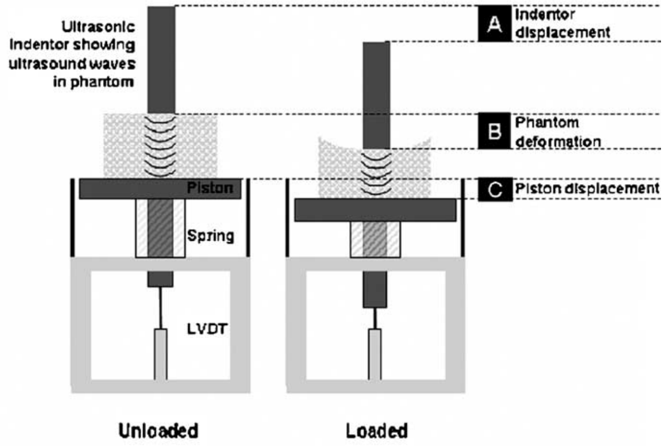

Fig 1. *Schematic representation of the tissue simulator used to test the accuracy of each of the indentation methods (not to scale). Displacement of the piston (C, simulating bone) is determined by subtracting the deformation of the phantom (B, simulating soft tissue) from the displacement of the indentor (A). Indentor displacement is determined by encoder counting of an electromechanical stepping motor in the rigid technique, an LVDT in the assisted technique and inductive transducers in the handheld technique.*

stiffness assessment reduce the diagnostic significance attributed to this procedure.

Despite these limitations, the clinical importance of quantifying tissue stiffness remains. Therefore, various investigators have developed technologies to improve on the limitations of manual tissue stiffness assessment. Although many of these techniques have attempted to replicate digital compression and measure the resulting external displacement response,[22-33] these bulk indentation techniques do not visualize internal tissue responses and are therefore limited in their ability to describe specific tissue properties. Several sophisticated techniques that achieve internal visualization (eg, elastography) now exist,[34] many of which use ultrasound.[35-42] These ultrasonic techniques also provide an additional improvement in that they may assist investigators in locating, and then returning to, a particular site of interest.[43]

To reduce error in ultrasonic indentation, early methods used rigid frames to advance ultrasonic transducers. Now, rigid frames are being superseded by other technologies, which may maximize cost savings, convenience, and the diversity of tissues that can be assessed. Unfortunately, there has been little information available to compare the accuracy of these different indentation methods. This information would be useful in determining which indentation techniques may have the greatest clinical utility.

Given the abovementioned, the purpose of this article was to use a specially constructed tissue simulator as a standardized testing condition to quantify the accuracy of 3 different techniques used to advance an ultrasonic transducer during indentation: a rigid, laboratory-based method (rigid), a less rigid system actuated by hand (assisted), and a totally free-hand system (handheld). It is hypothesized that the rigid method will have superior accuracy in detecting simulated bone displacement followed by the assisted and handheld methods, respectively. Ethical approval was not required by the host institute for this work.

Methods

Tissue Simulator

This study was designed to quantify the accuracy of 3 different techniques of ultrasonic indentation (rigid, assisted, and handheld) in their ability to quantify displacement of a rigid target. This was done by constructing a tissue simulator to approximate the deformation/displacement responses of soft tissue overlying a rigid bone (Fig 1). Specifically, the tissue simulator consisted of a gelatinous phantom that mimicked the sound propagation velocities of human soft tissue (1549 m/s propagation velocity, CIRS Inc, Norfolk, Va) placed over a rigid piston used to mimic bone. The acrylic piston, which was capable of reflecting ultrasonic waves, had its vertical movement governed by a spring and its lateral motion constrained by a piston housing. The gold standard reference value of piston displacement was obtained by an independent linear voltage displacement transducer (LVDT) attached directly to the piston.

Indentation Techniques

Rigid indentation was performed with an electromechanical stepping motor used to move an ultrasonic transducer in a linear path (Fig 2). Specifically, this technique used a linear stepping motor (Dual Motion Motor, HSI, Waterbury, Conn) with an integrated optical encoder (0.0127 mm per step per 8 encoder counts) attached vertically to a rigid aluminum gantry. Control of the motor's actuation and the sampling of the encoder signal were performed by computer-based hardware (National Instruments, Austin, Tex). Attached to the terminal end of the linear motor was a 16-mm-diameter, 5-MHz A-mode ultrasound transducer (V609 5.0/0.5, Panametrics, Waltham, Mass) operated by a computer-based pulse-receiver digital acquisition card (AD-IPR 1210, Physical Acoustics Corp, Princeton Junction, NJ). The transducer was operated at 200-V excitation and sampled at 100 MHz. Ultrasonic reflections were visualized by computer and their one-way transit time determined by a programmable threshold gate, which isolated signals of specific intensities (LabVIEW, National Instruments, Austin Tex). Isolated reflections were then sampled into the same digital acquisition system used to record encoder counts (1000 Hz) so that the transit time and motor displacement data could be recorded synchronously (National Instruments, Austin Tex). Indentor displacement was quantified using output from the optical encoder.

Assisted indentation was performed with a surgical limb positioner as a semirigid platform by which to apply

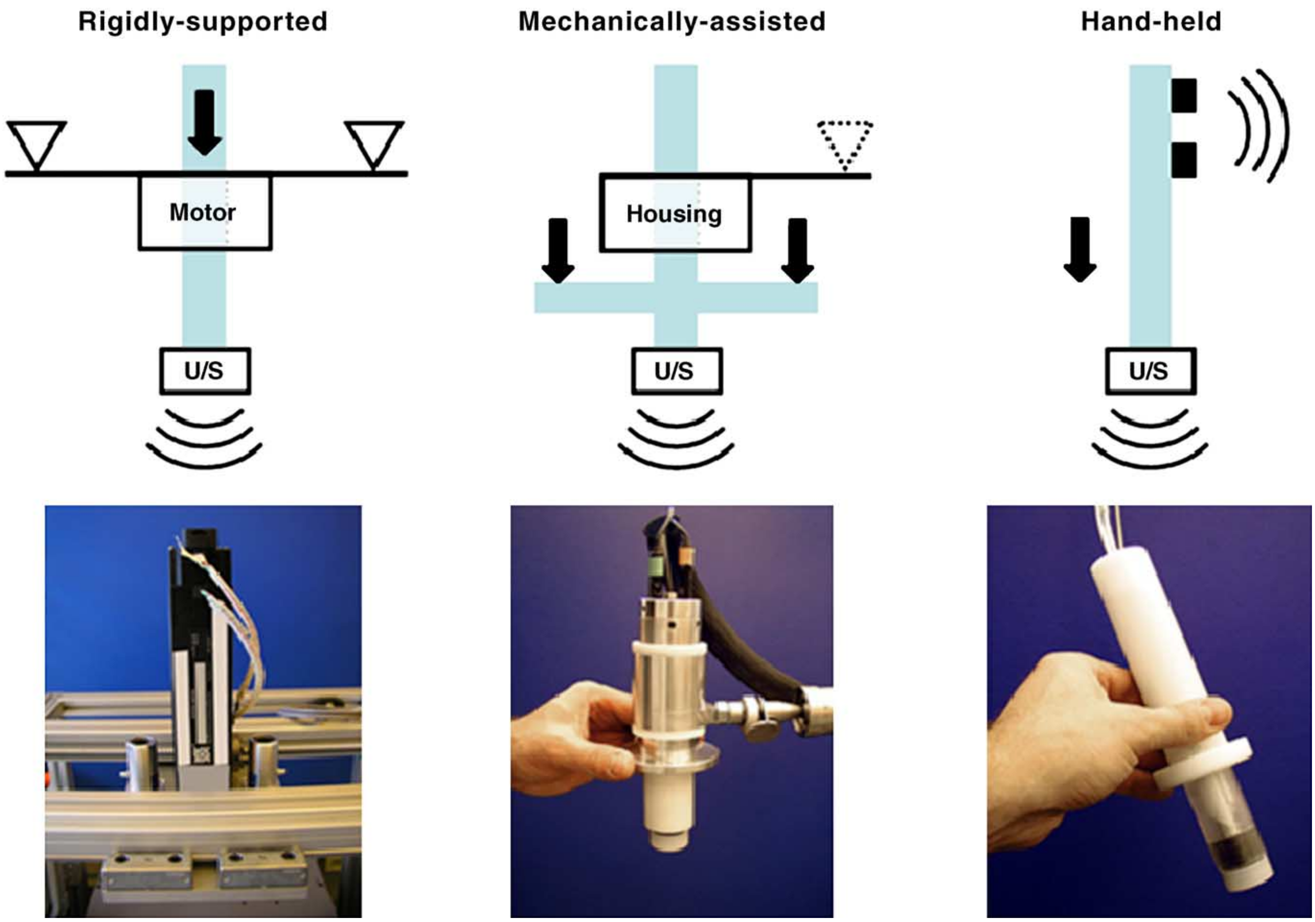

Fig 2. *Schematic representation of 3 methods used to actuate an ultrasonic transducer during ultrasonic indentation (not to scale).*

actuation of an ultrasonic transducer by hand (Fig 2). Specifically, a bushing was attached to a multiarticulated arm capable of being locked into position with compressed air (The Spider, Tenet Medical Engineering, Calgary Alberta, Canada). The bushing acted as a linear guide for a rod that could be actuated manually and independently from the bushing. To one end of the rod was attached a 16-mm-diameter, 5-MHz A-mode ultrasound transducer driven and recorded from in the manner described previously. On the rod's opposite end, an LVDT (0.1% error, MLT, Honeywell, Intertechnology, Don Mills, Ontario, Canada) was attached between the rod and the bushing housing to measure indenter displacement and sampled at 1000 Hz. Like the rigid technique, ultrasonic transit times relating to distance and actuator displacement were collected synchronously at 1000 Hz.

The handheld indentation technique used a solid plastic rod with a 16-mm-diameter, 5-MHz A-mode transducer mounted to its terminal end (Fig 2). This transducer was operated in the manner described previously. Fastened to this same rod were two inductive position sensors separated by 5 cm. The positions of these sensors were determined within an electromagnetic field (PCIBird, Ascension Technology Corp, Burlington, Vt). All position recordings were performed within the manufacturer's recommended recording volume. Three-dimensional coordinates of each sensor were recorded at the maximal rate for this technology (103/2 Hz). Output from the inductive position sensors was used to quantify indentor displacement and was collected simultaneously with ultrasonic data.

Each indentation technique was used to indent the tissue simulator to approximately 100 N on 10 successive trials using an indentation rate of 10 mm/s. For the rigid technique, this indentation rate was set as one of the parameters of the electromechanical stepping motor and an in-series load cell used to control the end point of indentation. In the case of the assisted and handheld techniques, an indentation rate nearing 10 mm/s was achieved by placing a bar graph moving at the desired speed next to the output of the transducer used to measure indenter displacement (LVDT for the assisted technique, inductive transducer for the handheld technique) then asking the operator to match the progress of the two visual displays. Because these two methods of indentation did not measure indentation load directly, the operator kept

Table 1. *Differences in measurement of simulated bone displacement (mm ± SDs) obtained experimentally from 3 ultrasonic indentation techniques (rigid, assisted, and freehand) and a gold standard (LVDT)*

	Rigid	Assisted	Handheld
Minimal difference (all points)	−0.43 ± 0.04	−0.21 ± 0.05	−2.05 ± 1.00
Maximal difference (all points)	0.78 ± 0.18	0.12 ± 0.07	−2.32 ± 0.68
Mean difference (all points)	0.00 ± 0.02	−0.04 ± 0.05	−0.08 ± 0.44
Mean difference (terminal point)	−0.01 ± 0.04	0.08 ± 0.7	−1.92 ± 1.06
Absolute minimal difference (all points)	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
Absolute maximal difference (all points)	0.78 ± 0.18	0.22 ± 0.04	2.72 ± 0.80
Absolute mean difference (all points)	0.14 ± 0.03	0.07 ± 0.02	1.15 ± 0.30

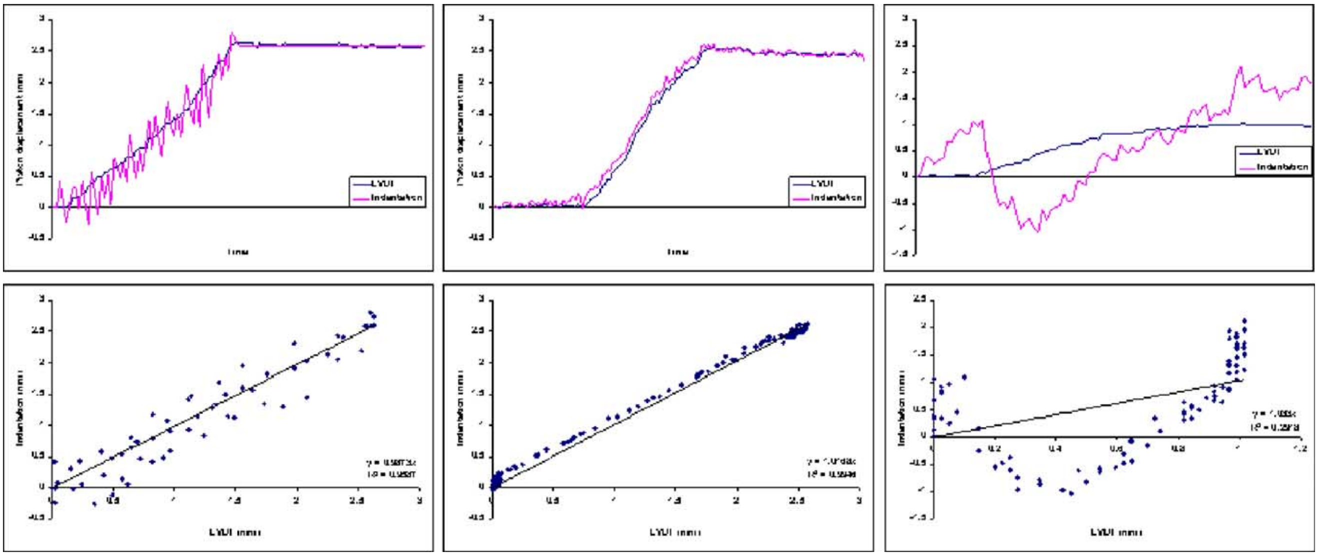

Fig 3. *Top, Experimental and gold standard (LVDT) measures of simulated bone displacement for the rigid (left), assisted (middle), and freehand (right) ultrasonic indentation techniques. Bottom, Scatter plots of gold standard vs experimental measures of simulated bone displacement for the rigid (left), assisted (middle), and freehand (right) ultrasonic indentation techniques. Linear trend lines were made to pass through 0,0.*

indenting at the desired rate until the piston displacement approximated the maximal displacement observed to occur when using the rigid indentation technique.

Calculations and Analysis

During the indentation, a continuous estimate of piston displacement was calculated for each indentation technique (Fig 1) by subtracting the phantom deformation (determined ultrasonically) from the total displacement of the ultrasound transducer (determined by encoder, LVDT, and inductive transducer, respectively). These estimates were then subtracted from the output of an additional LVDT used to measure piston displacement directly (reference gold standard). The difference between the experimental measures of piston displacement and the gold standard were found for all data points in each trial (signed and absolute values) as well as for the final data points in each trial (terminal points). The mean values of these measures were reported as overall accuracy and terminal accuracy.

A one-way analysis of variance with a Tukey post hoc analysis was used to determine if any significant differences were present between the estimated target displacements calculated by each of the 3 indentation techniques and the gold standard. Significance was set at an α level of .05.

Results

When indented, phantom deformation preceded piston displacement due to unequal stiffness between the two, indicating that piston displacement was not coupled directly to indentation displacement. During indentation with the rigid technique (the only technique able to record load information directly), the average deformation of the gelatinous phantom for a 100-N load for 10 indentations was 15.39 ± 2.40 mm, whereas the average displacement of the piston was 2.38 ± 0.28 mm.

Descriptive statistics for the difference between experimental measures and gold standard measures of piston

Table 2. *Analysis of significance in differences of accuracy between 3 ultrasonic indentation techniques (P values)*

All data points (signed)	
Rigid vs assisted	.90
Rigid vs handheld	.75
Assisted vs handheld	.95
All data points (absolute)	
Rigid vs assisted	.66
Rigid vs handheld	<.00*
Assisted vs handheld	<.00*
Terminal data points	
Rigid vs assisted	.98
Rigid vs handheld	<.00*
Assisted vs handheld	<.00*

Significance (*) is attributed at .05 or less.

displacement are displayed in Table 1. Line plots of the experimental and gold standard measures of piston displacement, which are representative of each indentation technique, are shown in Figure 3. In addition, Figure 3 displays representative data of gold standard measures of piston displacement (ie, bone) obtained by LVDT plotted against experimental measures obtained by the 3 ultrasonic indentation methods.

The mean coefficient of determination ($r2$) for experimental displacement vs LVDT displacement was 0.94 mm (±0.03 SD) for the rigid indentation technique, 0.99 (±0.00 SD) for the assisted technique, and 0.40 (±0.19 SD) for the freehand technique.

In considering all data points collected during indentation, the difference between the experimental measure of piston displacement and the gold standard measure by LVDT were not found to be significantly different between each indentation technique when the direction of the error (sign) was retained (Table 2). This was not the case when absolute values of the same error were analyzed. With absolute values, significance testing showed that the rigid and assisted data were not significantly different from each other vs comparisons of rigid to handheld and assisted to handheld (Table 2).

Discussion

This study used a tissue simulator capable of mimicking concurrent (yet unequal) soft tissue deformation and bony displacement during an applied load. These concurrent events are important to consider when a sonic reflector such as bone is used to estimate the thickness of the soft tissues during an applied load; should the applied load cause bone displacement at some point during soft tissue deformation, the tissue will appear erroneously compliant if the bony displacement is not considered. Although this circumstance may be unlikely with the low-magnitude loads used in ultrasonic indentation of knee cartilage[44,45] or with bones of large mass,[46] these same loads may be problematic if they cause displacement of the underlying osseous target, as what is likely the case in the foot[47] or in the spine.[48] Unfortunately, prior studies, which have validated ultrasonic indentation in these tissues did so by placing these tissues on an immobile ultrasonic reflector—a physiologically invalid condition unless the indentation load is less than the load causing target displacement. Instead of restricting the range of applied loads to a tissue of interest, our approach was to develop a technique that could be applied without assumptions about target mobility.[49,50] Therefore, this study was performed to establish the accuracy of various techniques in measuring bony displacement, which may occur during ultrasonic indentation of soft tissues.

A cursory examination of our results would suggest that each indentation technique has equal accuracy; there are no significant differences in the signed error generated by each indentation technique (Tables 1, 2 and Fig 3). A closer inspection of the data reveals that this is an aberration as the error generated by each indentation technique tends to fall equally on either side of zero. If the absolute values of error are analyzed instead, the true accuracy of each technique emerges.

The absolute error associated with the handheld technique is very high because it would appear that the underlying electromagnetic technology has difficulty in tracking indentation movements. Not an isolated finding, these large measurement variations have also been shown in other handheld indentation studies based on inductive technologies.[51] Although some handheld applications using non-inductive technologies have had some level of success,[52] many are still susceptible to angulation errors or use technologies such as optical tracking, which are expensive and difficult to use in clinical settings.[53]

The rigid indentation technique displayed a relatively small average absolute error of all data points as well as with terminal data points. This was also the case with the assisted technique. Although indistinguishable from each other statistically, the rigid and assisted techniques have characteristic signatures, as seen in Figure 3. Because the rigid technique uses a motor that applies discrete steps, the indentation load is not applied continually. Therefore, the applied load may build within the soft tissue phantom before reaching a point where the piston of the simulator reacts, thereby creating asynchronous estimates of piston displacement and indenter advancement. When the indentation approaches the maximal load and the loading rate nears zero, the experimental and gold standard measures of displacement then become synchronous. Although the rigid technique has been shown to exhibit an overall error of 7% in a cadaveric preparation,[35] the rigid technique may be less desirable if tissue properties between the terminal loading points are to be studied.

In contrast, the errors generated by the assisted technique are small and consistent in their sign throughout the indentation, the likely result of a more continuous load application. This is also reflected in the r^2 values of the assisted technique scatter plots (results section, Fig 3), which were higher than those of the handheld or rigid techniques. The accuracy of the assisted technique is likely a reflection of a stable, absolute reference for the piston housing achieved through a rigid support arm and precision machining of the rod/rod housing to reduce off-axis movement and the use of an LVDT to measure indenter displacement.

It should be noted that there are several limitations to testing indentation techniques with the simulator used in this study. First, piston displacement in the simulator is constrained to axial motion, a circumstance that does not exist in vivo. This is a minor concern because our prior work has shown that in unconstrained cadaveric preparations, the bony movement that occurs during ultrasonic indentation is primarily translation within the indentation axis—rotation is limited to 1° to 2°.[35] Therefore, because the primary response to indentation in situ is along the indentation axis, we limited the construction of our simulator to movement in this direction. Second, in creating the simulator, we had not intended to create an exact mimic of human tissue, only to create a simulator that approximated tissue response to loading by having soft tissue deformation precede bone displacement. However, it should be noted that the load response of tissues depends greatly on the loading site. For example, Lee and Evans[54] showed that 150 N applied to the spinous process of L4 in vivo produced up to 10 mm of absolute movement in the spinous process and just less than 2 mm of intervertebral movement. But if this same load were applied to the tissues lateral to the spinous processes as done by others,[26,35,43,48,55] then soft tissue deformation would be greater and the bone displacement decreased. We chose to build a simulator designed to model transverse process loading rather than spinous loading. As a result, the bony displacement created in the simulator for a 100-N load was less (2 mm on average) than if spinous loading were modeled. Although the displacement of the "bone" could have been controlled by selecting a specific stiffness of the piston spring, the need to have an accurate measure of phantom propagation velocity restricted our ability to designate the stiffness of the phantom. That being said, on average, the change in height of the soft tissue material was 15 mm, a value similar to what is observed in human population studies we are now conducting.

Although the accuracy of the rigid and assisted indentation techniques was statistically similar, the operation of each technique is substantially different. Compared with the assisted technique, the rigid technique occupies a greater volume, uses more expensive components, and is more difficult to operate. These factors reduce the clinical viability of the rigid technique greatly.[48,56,57] Given these range of factors, we recommend that the assisted technique of ultrasonic indentation be explored further as a clinically relevant tool for assessing tissue stiffness.

Conclusions

This investigation quantified the accuracy of 3 different techniques used to advance an ultrasound transducer for the purposes of ultrasonic indentation. Using an apparatus to simulate deformable soft tissues overlying displaceable bone, it was found that the rigid and assisted indentation techniques showed the greatest accuracy in measuring the displacement response to an applied load. Because the assisted indentation was not found to be significantly different in its accuracy from the rigid technique, which is a cumbersome and costly approach, the clinical utility of the assisted technique should be explored. The handheld technique was the least accurate of all, exhibiting an error magnitude that may preclude it from use in human ultrasonic indentation applications.

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Practical Application

- The rigid and assisted indentation techniques provided the greatest accuracy.
- Of the rigid and assisted techniques, the assisted technique was easier to use.
- The handheld technique was the least accurate.

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