Sonometric Triangulation for Seated Pelvis Orientation

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ABSTRACT

Pelvic orientation in vehicles is crucial for preventing injuries and creating safer vehicles and restraint systems. A better understanding of pelvic orientation could provide more accurate anthropomorphic test device (ATD) models of underrepresented populations such as obese individuals, children, and small females. Sonomicrometry is the use of piezoelectric transducers that transmit ultrasound signals to each other to measure the distance between them. These signals may be aggregated using triangulation. In this experiment, ultrasound crystals were secured to the surface of a porcine surrogate to evaluate pelvic movement. This data was then processed using Sonometrics software to generate a 3D model of four static positions and three dynamic tests. The test was validated using a camera and a 3D measurement arm (CMM) to validate XYZ positions. This paper discusses how this method could be helpful for developing more accurate ATD models, preventing fatalities in vehicle crashes.

INTRODUCTION

In 2019 there were ~36,000 fatalities owing to motor vehicle crashes and an estimated 2.74 million injuries (NHTSA 2020). The primary goal of automobile safety is to reduce this annual toll. A crucial element in understanding how the human body reacts in a vehicle crash is pelvis orientation. For example, decreasing the pelvic angle by having the subject lower their knees in vehicle seating may reduce the potential for injury (Nishida, et.al 2021). By understanding pelvis orientation in the seat of the vehicle, improved restrain mechanisms can be developed to provide safer occupant compartments, reducing morbidity and mortality. Often, determining the detailed position of the thighs/pelvis/torso is difficult, particularly in normal belted seated posture in current automobile seats. Bony landmarks are generally occulted by the belt, seat, and other details of subject anthropometry, clothing and vehicle geometry. Current measurement techniques for determining bony landmarks in pelvic position are generally based on angle calculations which do not consider the interaction of the bony structure and their relationship with the surface (Mandalidis et.al 2022). For example, obese occupants, often at higher risk of pelvic and abdominal injuries, have difficulty obtaining proper fit in restraint systems that generally target midsize male occupants (e.g. Forman et al., 2009). During vehicle crashes, obese occupants may experience severe forward motion of the head and pelvis while also experiencing backwards torso rotation resulting in unfavorable kinematics for lap belt restraints leading to severe injury. One of the main challenges of creating models that can accurately represent different body weights, sizes,

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and different sexes is understanding the seated anthropometric of occupants. Vulnerable populations such as obese, small women, pregnant women, etc. are largely poorly studied, especially pelvis orientation in restrained and seated postures.

Sonomicrometry is a measurement technique that uses two or more piezoelectric ultrasound crystal transceivers that oscillate and transmit high frequency signals at the material speed of sound through a transmissible solid or aqueous solution. The distance between crystals is determined by the time of flight for the transmitted signal to reach a receiver crystal (Salzar et al. 2003). Using a network of these devices and triangulation, these sensors can give accurate static and dynamic information on surfaces and inside tissue (Alshareef et al. 2018). This study uses sonomicrometry to establish a measurement paradigm to assess surface position of the thighs/pelvis/torso to assess anthropometry and geometry of humans in seated posture where the skin surface is occulted by structure and restraints. A 3D measurement arm (CMM, Romer Absolute 7-Axis SI, Hexagon) was used to verify positions of the sonometrics crystals statically (cf. Kovac et.al., 2001). This measurement paradigm has the potential to dramatically improve understanding of the details of seat and restraint geometry and influences of anthropometry and seating/restraint characteristics on injuries from car crashes, especially for vulnerable populations.

MATERIAL AND METHODS

Physical Testing

A sonomicrometry system (Sonometrics 16 channel system, London, Ontario) was used to provide distance measurements between discrete points on a porcine cadaveric surrogate. Porcine cadavers were procured from a local butcher and are not subject to IACUC protocols. Twelve, 2mm, sonometric crystals were sutured onto the surface of the porcine surrogate in the region of the thigh, pelvis, and torso. The crystals were placed in an arrangement of repeated triangular formations to promote accuracy in triangulation with an average 80mm distance (Figure 1). This distance was suggested by the manufacturer as best for baseline length vs signal strength.

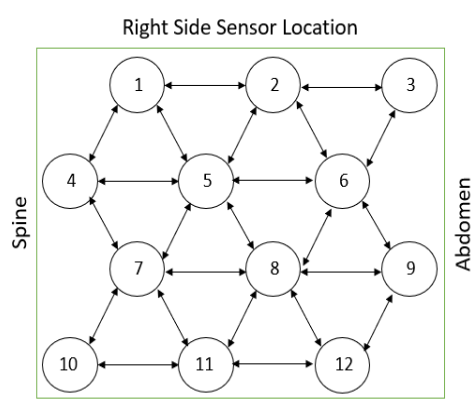

Figure 1. Schematic of sonometric crystal placement on the porcine surrogate skin. Note: triangle base structure is optimal for errors and sensitivity with the Sonometrics system.

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Ultrasound gel was used as a couplant around the crystals and skin of the surrogate, aiding in the transmitting, and receiving of signal. External plastic wrap was used to ensure the crystals and gel remained in place and had continuous contact with the skin. The surrogate was secured to an adjustable table (Figure 1) with the spine flat on the immobile table portion and legs on the adjustable portion allowing for movement during testing.

Error! Reference source not found. shows the set-up of the testing area. A highspeed camera (Phantom Miro LC-310) was used to capture the motion of the pelvis during testing and the placement of the crystals. The 3D coordinate measuring machine (Romer-CMM model 7-Axis SI, Hexagon, Stockholm) was used to verify the three-dimensional data collected using the Sonometrics system. The surrogate was secured to the table using a ratchet strap under the front limbs. The back feet of the surrogate were not secured to the table.

Four hip angle positions were tested as shown in Figure 3Figure 31 with position 1 being the highest point of the adjustment table with the angle closest to 90 degrees and position 4 being the lowest point of the adjustment table with the angle closest to 180 degrees. The adjustment table was set to each level for 3 trials. Data was collected to determine the XYZ position of each crystal using the Sonometrics system. The CMM arm was used to acquire measurements of 4 static markers on the table and the positions of the 12 crystals, when accessible to the arm. CMM measurements were taken before each trial.

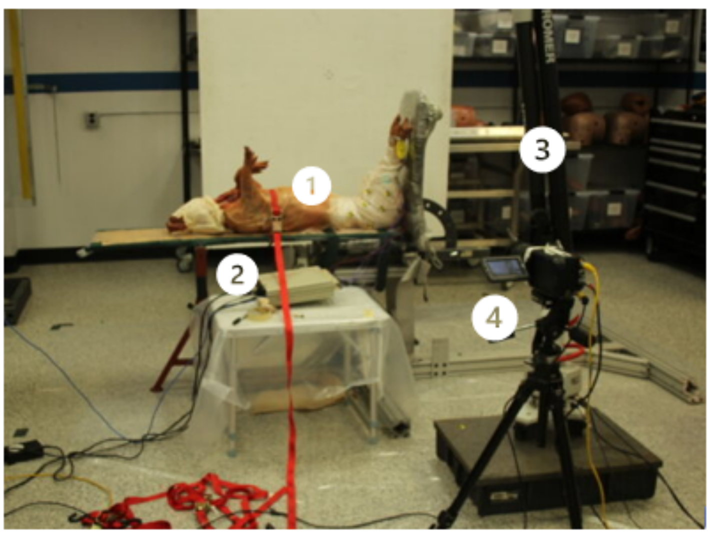

Figure 2. Experimental configuration with the surrogate on the adjustment table[1], the Sonometrics data acquisition interface[2], the CMM arm[3], and the high-speed camera[4].

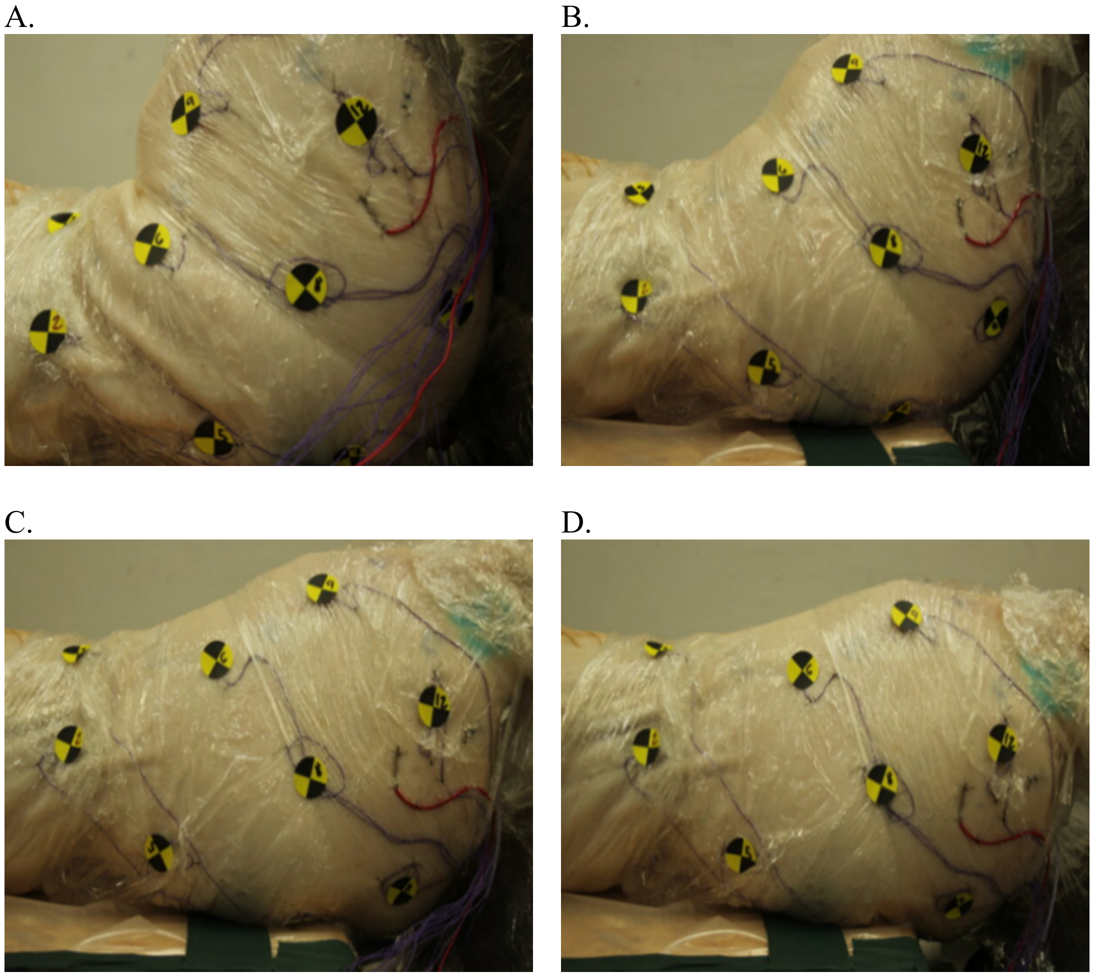

Figure 31. Four static positions of the subject using the adjustment table with crystals attached to the hip. A. Position 1, B. Position 2, C. Position 3, D. Position 4

Following the static testing, three trials of dynamic testing were completed. The table was manually moved from position four to position one to position four while sonomicrometry data was recorded, three times per trial. Video tracking was used for the dynamic movements and the data was recorded using the Sonometrics software (SonoLab). CMM measurements were taken at the beginning and end of each dynamic trial. Data was collected at a sampling rate of 153 Hz with a transmitting pulse of 406.25 ms and speed of sound set to 1.59 m/ms.

Procedure for Data Analysis

SonoSoft (Sonometrics analysis software) was used to analyze signal data gathered from each crystal. 24 signals were recorded, redundant signals were used in the analysis for the most accurate results. Figure 4Figure 2A shows the raw signal from crystals before filtering using a median and averaging filters. The filtered signal is shown in Figure 4B. Signals that provided qualitatively poor data as assessed by sudden unstable jumps and noise were marked as bad and

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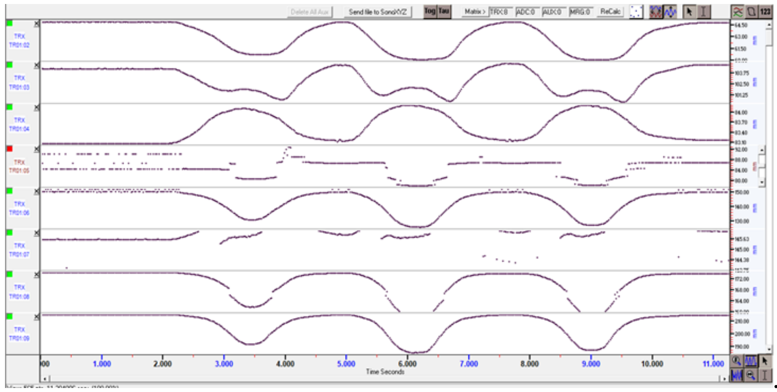
are not included in the results. Filtered signals were sent through SonoXYZ software that converted the signals into a 3D model. Additionally, SonoXYZ allows for the XYZ data of all the crystals to be gathered and shows how the data changes throughout the test.

A.



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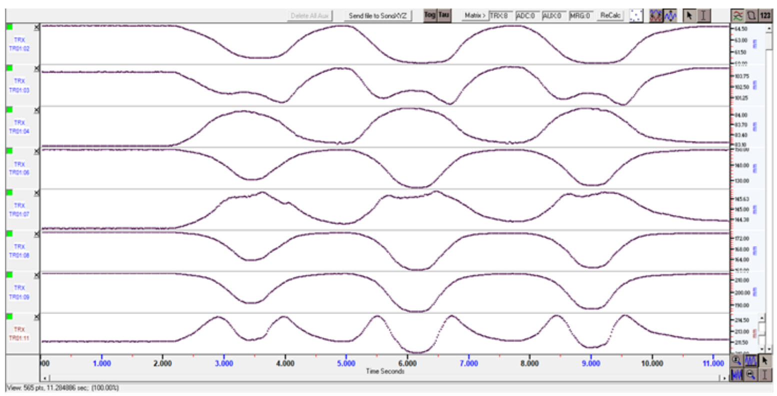

Figure 2. Waveforms shown on Sonometrics software A. Data taken before filtering and software infilling. B. Data after filtering and infilling.

RESULTS

Using the SonoXYZ software, 3D models for both static and dynamic tests were created. The 3D models use the same coordinate system provide consistent orientation of the model. Figure 53igure 5 shows the 3D models that were generated for each static position. As noted above, there were three trials that were recorded for each static position. After filtering, the best trial was chosen to generate the 3D model. For the figure below, the diagrams are oriented differently from each other to best show the movement of the crystals during the testing. The figures show that each of the positions are different compared to the others, this is expected since there is qualitative relative motion between the sensors owing to the change of global position. Lines demonstrating the triangulation method used to place each crystal on the specimen were added to aid in visualization.

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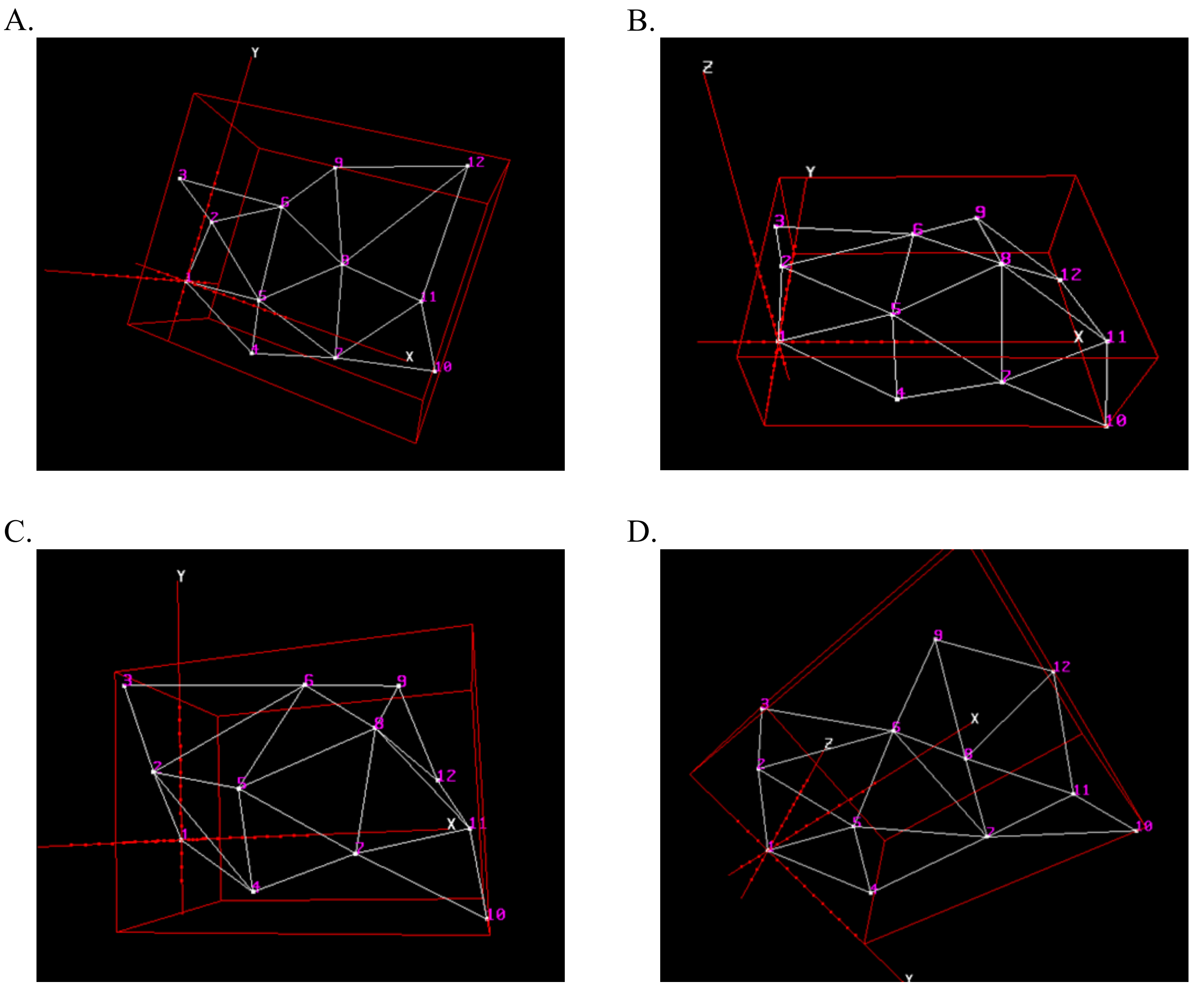

Figure 53. 3D models of each static position created using Sonometrics software. A. Static position 1 of Right Side. B. Static position 2 of Right Side. C. Static position 3 of Right Side. D. Static position 4 of Right Side.

Figure 6 shows the 3D model of dynamic test 1. Distance signals are obtained for most of the adjacent sensor triplets across the tissue. The dynamic motion can be seen for crystals 3 and 9, circled in yellow, which get closer to each other during the contraction. Crystals 4 and 7 are located on the spine, circled in blue, maintain relatively constant position as expected from there relatively fixed position. In this test, the figures show crystal 10 having a greater vertical position (global x coordinate - ~5%) than crystal 11, circled in green. Owing to the orientation, this was not expected and will be discussed later in the limitations section. In contrast, dynamic motion of crystals 3 and 6, on the abdomen, move in appropriately in concert. Crystal 5 on the lateral side has motion that is also appropriate to the observed thoracic flexion and extension. Models of dynamic tests 2 and 3 were also created (see Appendix).

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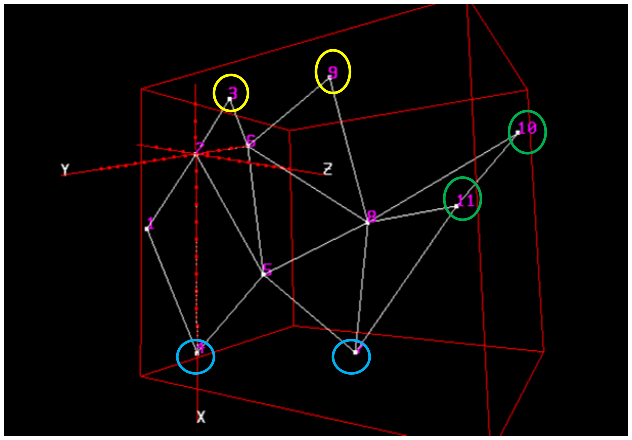

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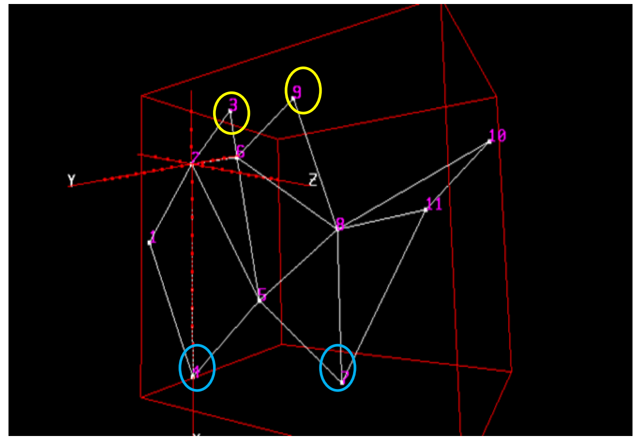

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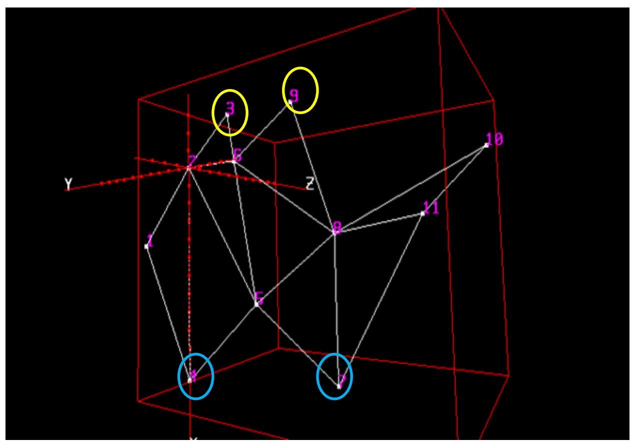

Figure 4. 3D models of dynamic test 1 at three different points during the contraction. A. Right side dynamic test 1 starting position. B. Right side dynamic test 1 middle of contraction. C. Right side dynamic test 1 top of contraction.

Comparison of Sonometrics and CMM arm

To determine the accuracy of the Sonometrics device, data was collected by the CMM arm. Here, the CMM arm as a “Gold Standard” for such measurements, though we discuss the limitations of the CMM for this purpose in the limitations. Reciprocal channels of the Sonometric device (e.g. crystal 1 send – crystal 2 receive vs crystal 2 send – crystal 1 receive) did not have identical numeric values, though they were often different by less than `%. So, the average of each Sonometric channel pair was taken and compared to the CMM arm data for all static and dynamic testing. Figure 5igure 7 displays the percent difference of the averaged channel pair distance calculated by the Sonometrics device compared to the CMM arm data of the static trials. Typical errors are less than 5% with a mean error of 2.4±1.3 %.

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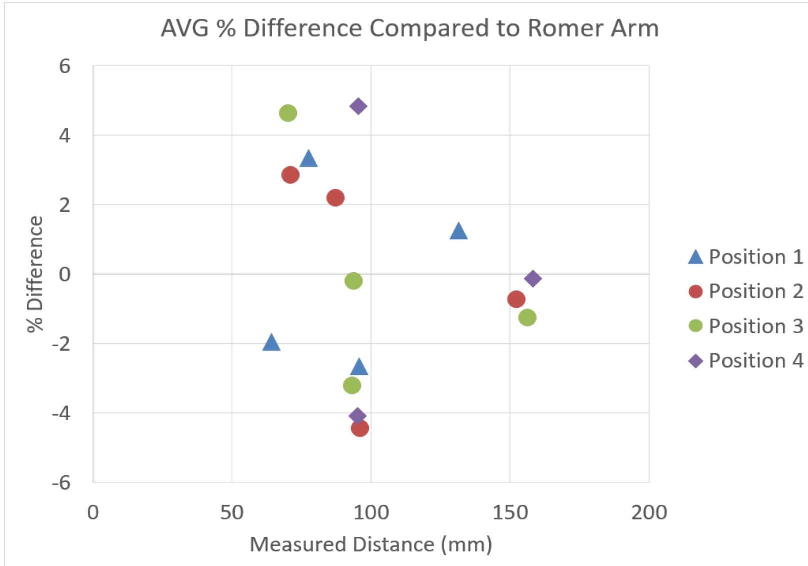

Figure 5. Percentage error between Sonometrics data and CMM arm during static testing. Mean error from Sonometrics to CMM measurements is 2.4±1.3 %.

The dynamic testing compared the results across the three trials for the start position (P1) and end position (P2) which are nominally the same position. Figure 6igure 8 displays the percentage difference between the measured value of the Sonometrics device and the CMM arm for a selected sensor set for the two nominally repeated postures (Trial 2). This analysis shows sensor to CMM average differences of 1.1±0.8% across the repeated posture.

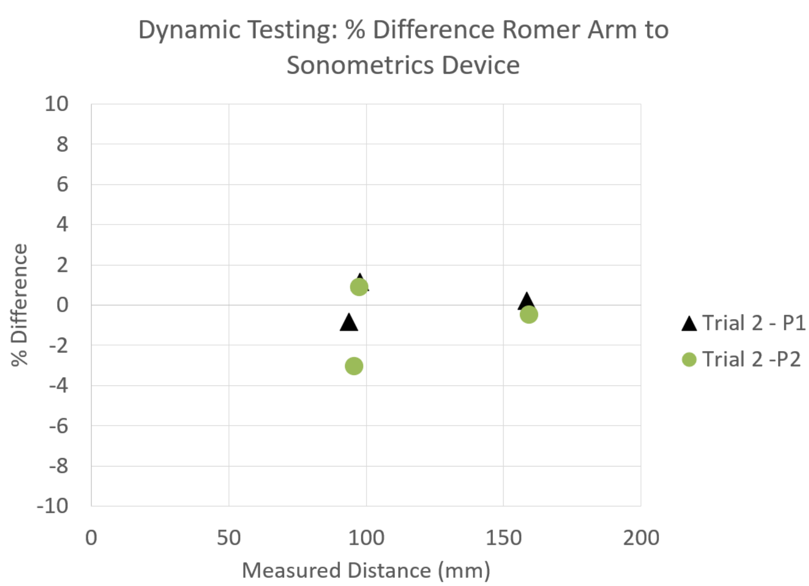

Figure 6. Percentage difference of start and end dynamic testing data between Sonometrics and CMM arm. Average difference between sensors is 1.1±0.8%.

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DISCUSSION

This study is the first to demonstrate sonomicrometry across macroscopic distances with skin surface coupling. This supports the use of sonomicrometry to create a 3D model of pelvic movement. Distance errors with average less than 2.5% were demonstrated compared with CMM arm measurements used as a gold standard. Four static trials in different positions and three dynamic trials were conducted with the crystals on the right side of the surrogate demonstrate qualitative and quantitative agreement with the gold standard during changes in the hip angle between different positions. We also demonstrated qualitative repeatability among trials with motion.

In contrast to previous studies (e.g. Mandalis et. al., 2022) which used two laser distance meters, a ruler, and Euler/Cardan calculations to determine pelvic angle in a static position, this method uses sonomicrometry to determine measurements from which pelvic angle can be derived. The advantage of this technique is the potential for use in both visible and visually occulted scenarios, typical of automobile seating positions and anthropometric postures. This method can also be extended to human subjects making it a potentially more accurate and informative alternative to characterize human hip position and movement statically and during vehicle crash situations.

Triangulation and Error

Triangulation was used to determine placement of crystals in 3D space. Triangulation requires adequate of coverage of the desired area to record the angle changes accurately (Alshareef et.al., 2018). To determine a single crystal location, the distance between it and two reference crystals are required. Error in the reference distances may cause substantial calculated errors in the internal angles for a given sensor triangle and derived edge positions (Sunderhauf et. al., 2007). Throughout testing, there were many cases where sensor noise or lack of sensor signal prevented use of the corresponding distance in triangulation. This error can be reduced by adequate coupling, limiting the distance between sensors, choosing triangles that are nearly equilateral, optimizing the strength of the transmitted signal.

LIMITATIONS

The coupling of the crystals with the skin is essential for the performance of the sonomicrometry system. Reduced performance was seen when the coupling was inadequate. This is likely the main source of sensor noise, and dropouts. This can be improved using a structured support mesh with low impedance mismatch materials that provides optimal coupling to the skin. For example, a skin-tight fabric or polymer with included ultrasound couplant is a potential solution to these issues. Further, the system is qualitatively sensitive to transmit pulse and amplitude. Optimization of these parameters is another attractive target for system improvement. Additional accuracy may be obtained using additional crystals since the application to thigh/pelvic/torso surface geometry is relatively slow for the sonomicrometry sampling procedure. An additional limitation is the assumed speed of sound in tissues. The speed of sound through pig

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skin may be different human skin. However, porcine skin has similar properties to human skin (cf. Ranamukhaarachchi et.al., 2016).

An important limitation on this study is the CMM arm used for the gold standard. The CMM arm has some measurement errors associated with it. The XYZ coordinates from the CMM arm are gathered by manually placing the tip of the CMM arm onto the crystal. The Sonometrics crystals are 2mm in diameter, placement of the CMM arm in the same spot was not possible, leading to a ±1mm error from that alone. The surrogate underneath the crystals was deformable depending on the pressure applied by the user. The CMM arm tip pushed the crystal into the surrogate skin at an unknow pressure, which could cause ±1-2mm error in the three-dimensional data values. The maximum error of the CMM arm is approximately ±3 mm, changing the distance between one length of the triangulation leading to 3 mm difference causes a 3.33 percent error in the CMM arm data.

Future Work

For future work, the calibration between the measurement gold standard and the Sonometrics software should be optimized for better comparisons of results. Laser scanning can be used in the future to get a more accurate determination of the location of the crystals. Ideal crystal placement (~80 mm equilateral triangles) should also be established to improve results. Crystal placement would affect the number of good distance traces that each receiver would have to avoid trilateration errors within the SonoXYZ software, leading to a more accurate 3D model.

Using the plastic wrap alone to keep contact between the crystals and the skin was not optimal for each crystal. The plastic wrap shifted during testing and provided different pressure amounts to crystals. We are developing a flexible clothing framework with incorporated crystals that will improve the contact to the skin, improving the transmitting and receiving of signals.

Additional advanced techniques with the ultrasound crystals are feasible, including the determination of nearest bony landmark to a given crystal transmission from reflected impedance mismatch. Such techniques have the potential to increase the fidelity of the surface crystals. The Sonometrics device reads the first received signal as the distance between crystals. With bony structures the reflected signal can reach the crystal first and display the incorrect distance. An inhibit delay is added to counter this effect. However, knowing the distance of the bone in relation to the crystal will improve the filtering process of the Sonometrics data.

CONCLUSIONS

This study demonstrated the feasibility of sonomicrometry to assess surface positions on skin with potential applications to thigh/pelvic/torso seated surface positions. Using the data captured and triangulation, the angles between the crystals can be calculated to determine the pelvic angle and other aspects of seated and restrained subject. This method could be used to accurately measure the pelvic angle of vulnerable populations to allow for a more accurate ATDs and computational models supporting injury biomechanics for these populations. A more accurate

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model would allow for car manufacturers to better simulate how these populations perform in a real-world crash, allowing for the development of better restraint mechanisms (Carroll 2010). Future studies should include improved skin to Sonometrics interfaces and coupling, improved gold standard comparison and optimized system response.

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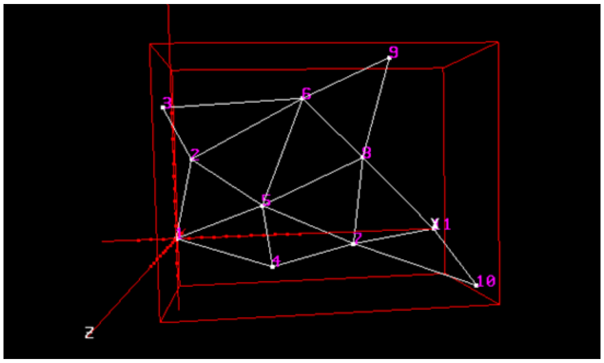
APPENDIX

A.



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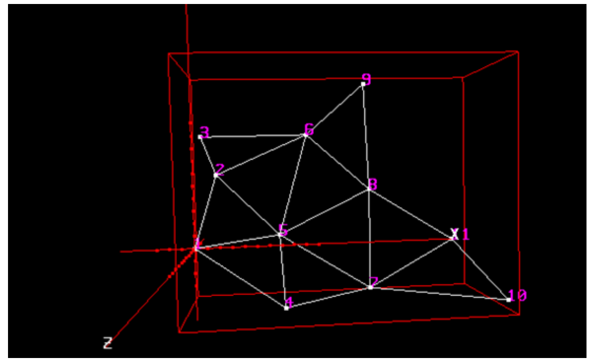

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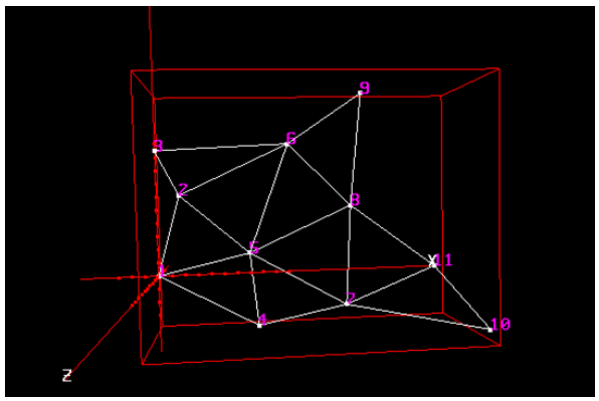

Figure 9: 3D models of dynamic test 2 at three different points of the contraction. A. Right side dynamic test 2 starting position. B. Right side dynamic test 2 middle of contraction. C. Right side dynamic test 2 top of contraction.

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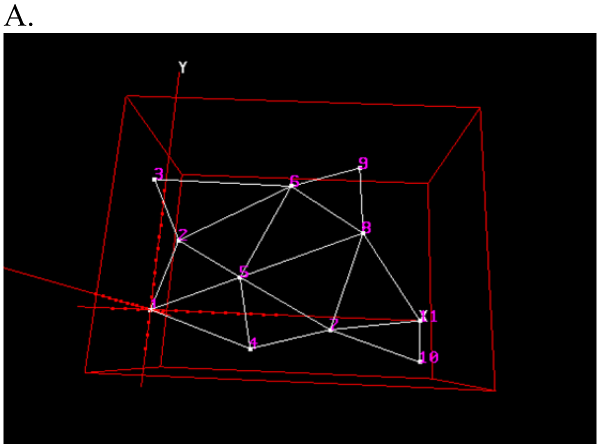

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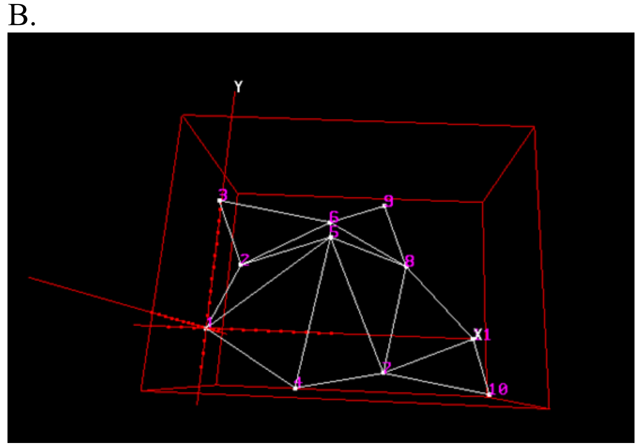

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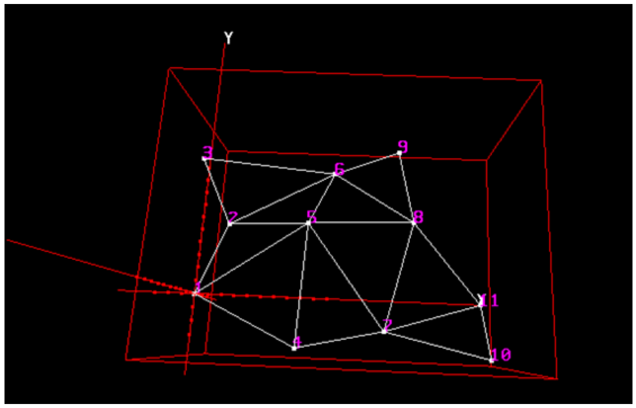

Figure 10: 3D models of dynamic test 3 at three different points of the contraction. A. Right side dynamic test 3 starting position. B. Right side dynamic test 3 middle of contraction. C. Right side dynamic test 3 top of contraction.

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