Phantom Study of Arterial Localization using Tactile Sensor Array and a Normal Vs. Shear Pulse Pressure Propagation Method

Rory Hampson*, *Member, IEEE*, Alistair Lawley, Gordon Dobie

Abstract— Objective: **Locating the radial artery reliably is a key challenge in reducing patient risks from complications in Trans-Radial Access, which is an important clinical method for catheterization, cardiac monitoring, and neuroendovascular procedures. New tactile sensing technology is being developed to bridge the skill, cost, and performance gap between ultrasonic needle guidance, and manual palpation, for use in developing countries. This paper further develops tactile artery localization with a novel algorithm for arterial localization based on the properties of a curved tactile sensor array.** ***Methods:*** **Using tactile sensor insensitivity to shear loading, coupled with a radial pulse wave propagation path, the position of the artery can be found at the intersection of a normal and tangential vector from the array corresponding to maximum and minimum pulse pressure measurement locations respectively. This was validated in a simple silicone phantom study** ***Results:*** **The proposed method measured with MAE= 0.58±0.25mm whilst the artery is within range of the tactile array, compared with 0.81±0.57mm for a comparative method of simple pulse localization. This showed improvement in arterial localization and repeatability, and was within 1 arterial radius, expected to reduce the risk of missing the artery, or perforating the side wall.**

Clinical Relevance— **Robust and repeatable arterial localization is important for reducing the failure rate of trans-radial (and other arterial) procedures, and thus reducing the risk of harmful complications.**

I. Introduction

Trans-radial Access (TRA) is preferred for performing coronary angiography and percutaneous coronary intervention over other sites [1], as well as being used for catheterization [2] and providing A-line blood pressure (BP) standards. It is preferred for its generally lower risk of complications compared with other arterial sites [3], however it is not completely without risk. Complications exist, such as finger necrosis [4], hematoma, arterial puncture, and arterial occlusion [5] amongst other complications [2].The TRA failure rate is in the order of 6.8% [6], where failure either causes complications or requires a second attempt, and although there are medical predictors of failure many come down to poor needle application [7]. While ultrasonic needle guidance does help with this [8], ultrasound has a relatively high skill burden, on top of the high upfront cost of the equipment. This is fine for developed healthcare systems, but developing systems still rely on manual palpation, bringing patient complications as well as risk of accidental injury to the clinician. New needle guidance technology based on capacitive tactile imaging [9] is under development as a low cost alternative to ultrasound in this application as in other clinical applications for the developing healthcare world [10].

A. Tactile Arterial Localization

Tactile arterial localization is an alternative to ultrasound [8] that is more sensitive than manual palpation, and is currently under development in the form of SmartTouch (Medical Tactile Inc., US-CA). This is shown in Figure 1. SmartTouch is a system that uses a tactile array to detect arterial pulse pressure on the skin, thus localizing the artery. It then indicates the position to the clinician using an LED marker, whilst also acting as a finger guard to protect the clinician from accidental injury.

It has been observed that this still led to failed application in some cases, particularly when the array is badly aligned and so a more robust localization method is to be developed. For this, the flat array used in early versions of SmartTouch is substituted for a curved 2x9 array, SN9490 (PPS UK Limited – GB) to allow for greater flexibility. For repeatability, the array is to be mounted on a robot manipulator for this work.

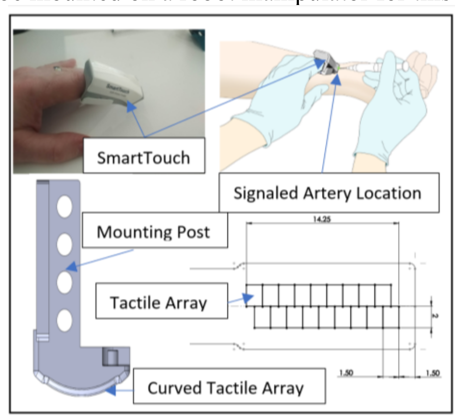

Figure 1 - SmartTouch artery finder. Fingertip mounted tactile sensor used to locate radial artery. (PPS UK Limited, - GB).

II. Scope and Objective

This paper shall introduce a new method of tactile arterial localization, taking advantage of capacitive tactile element properties which will be tested in a robotically controlled phantom study replicating a needle guidance application. This work will not cover clinical TRA, focusing on localization.

*Research supported by PPS UK Limited (GB) and Medical Tactile Inc. (US -CA)

Rory Hampson is with the Centre for Ultrasonic Engineering (CUE), University of Strathclyde, 204 George St., Glasgow, G1 1XW (correspondence e-mail: rory.hampson@strath.ac.uk).

Alistair Lawley is with the Future Ultrasound CDT (FUSE), University of Strathclyde, GB. Gordon Dobie is with the Centre for Ultrasonic Engineering (CUE), University of Strathclyde, GB.

III. Arterial Localization Method

Previous iterations of the design located the artery laterally only, by assuming the artery was directly beneath the tactile element detecting the maximum pulse amplitude, typically the closest element to the artery, labelled as point 'N' in Figure 2. This can produce lateral position errors greater than the arterial diameter depending on the artery depth, as shown in Figure 2, which can lead to failed needle insertion.

The bandwidth of these tactile sensors is too low to perform any phased array techniques [11], based on pulse arrival time at different sensor elements to localize the artery, as the pulse wave is detected within 1 sample by all elements.

As such, a novel method of localization is proposed that takes advantage of the tactile sensor insensitivity to shear loads. Considering Figure 2, the pulse pressure wave from the artery propagates radially towards the sensor, resulting in maximum pulse amplitude measured at sensor element 'N', and minimum at element 'T' on the array. Point 'N' experiences a maximum as the wave is propagating normal to the element and so the element has high sensitivity. Point 'T' measures minimum as the pulse wave propagates tangentially to the sensor at this point and so the sensor is insensitive to the pulse. These two points can be used to triangulate the location of the artery w.r.t the sensor array axis.

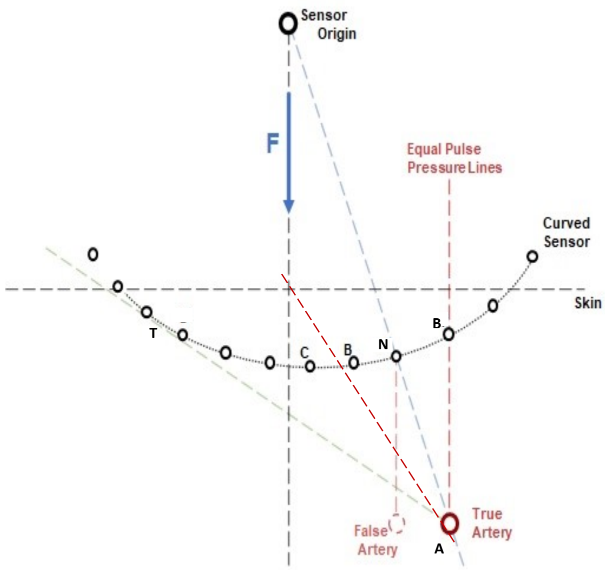

Figure 2 - Arterial Localization Diagram. The tactile sensor is pressed into the skin, normal and shear pulse vectors can then be drawn to find the position of the artery w.r.t. the sensor origin.

A. Normal Pulse Pressure Vector

The normal vector is found by constructing a line between the sensor curvature origin and the point of maximum pulse amplitude detected by the tactile array. This is further improved by interpolating pulse amplitudes between elements using a spline fit. This line is by definition normal to the sensor array, and is directed at the true artery location as shown in Figure 2. This is constructed at point 'N' in Figure 2. This line will naturally move around as the sensor array moves w.r.t. the artery or skin surface.

B. Shear Pulse Pressure Vector

The shear vector is a constructed line tangential to the tactile sensor array at the point where detected pulse amplitude is zero, and static compressive load is non-zero indicating that the sensor is engaged with the tissue. This is constructed at point 'T' in Figure 2. This is further improved by interpolating between elements using a spline fit to find the point where pulse pressure reads zero. Elements that are not touching the skin, so will not read pulse pressure, are excluded.

These lines intersect at the artery, point 'A', which through line construction gives the position of the artery (x_A, y_A) relative to the sensor origin as shown in Equation 1. (X_0, Y_0), (X_N, Y_N), and (X_T, Y_T) are the sensor origin, and points 'N' and 'T' respectively, which are known from sensor geometry.

$$x_A = \frac{Y_T + \left(\frac{X_0 - X_T}{Y_0 - Y_T}\right) X_T}{\left(\frac{Y_0 - Y_N}{X_0 - X_N}\right) + \left(\frac{X_0 - X_T}{Y_0 - Y_T}\right)}, \quad y_A = \left(\frac{Y_0 - Y_N}{X_0 - X_N}\right) x_A \qquad (1)$$

C. Indenter Depth/Angle Offset

In some cases it may be useful to know the artery depth w.r.t. the skin surface, rather than beneath the sensor array. Additionally, it cannot be guaranteed that the sensor will be used axially at all times.

The depth of the sensor array is estimated by fitting a gaussian curve to the static loads measured between each element, where the height of the curve is roughly proportional to the insertion depth.

The angle offset is found by rotating arterial position estimated from the previous steps by some angle θ where θ is the angle between the point of maximum static load (point C from Figure 2) and the central axis. This is a necessary step as the needle insertion assumes the needle is axially aligned, and so the rotation shifts the reported arterial position to the nearest axially aligned needle guide.

IV. Experimental Method

Testing of arterial localization, and comparison with previous methods, was done in the 'x' axis only as this allows for comparison. This was done using the setup shown in Figure 3. The tactile sensor array was mounted onto a MECA500 robot arm (Mecademic Robotics – CA). This repeatably presses the sensor into an arterial phantom in 3 distinct locations w.r.t. the artery. These are with the array centered on the artery, the array axis offset 5mm from the artery (similar to Figure 2, and the array misaligned 10mm off axis such that the artery is not under the array. This simulates performance over a range of use cases.

The arterial phantom is a simplified silicone block, made from Ecoflex 00-30 (Smooth-On Inc., US-PA), with an artery made from 2.5mm ID heat- shrink tubing (RS Components Ltd. – GB) to approximate a suitable diameter [12], [13]. An arterial pulse wave is delivered using an arterial puncture wrist circulation pump, number 11351-999 (Kyoto Kagaku Co. Ltd. – JP). Water was supplied via a feed tank, that could be raised to vary the hydrostatic pressure. Waste water drained into a waste tank.

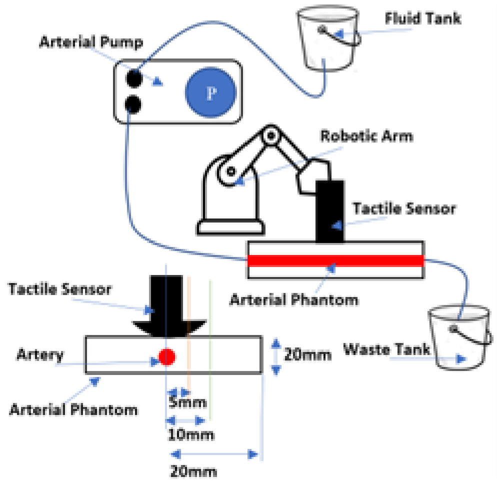

Figure 3 - Experimental Setup Diagram. The tactile sensor is pressed into the phantom in 3 different locations w.r.t. the artery by the robot arm: Centered, 5mm offset, and 10mm misaligned.

The robot arm pressed the sensor array into the 3 locations over a discrete depth range of 2-10mm in 2mm steps. 5 pulses were captured at each depth increment to provide a single measurement. 5 measurements at each location and depth were averaged to obtain the tracking trend. Sensor depth measurement was compared between the robot estimate and the prescribed method at the misaligned position only as it is not affected by pulse propagation, and to avoid interference from the artery. The phantom material was relaxed mechanically between compression runs.

V. Results

The results of the localization and compression depth measurement trials are shown in Figure 4. For the cases where the artery is beneath the tactile array (centred and 5mm offset), the results show that the proposed method is effective in estimating the horizontal distance between the sensor axis and the arterial centre with total errors being within the arterial limits indicated by the black lines [13], [14].

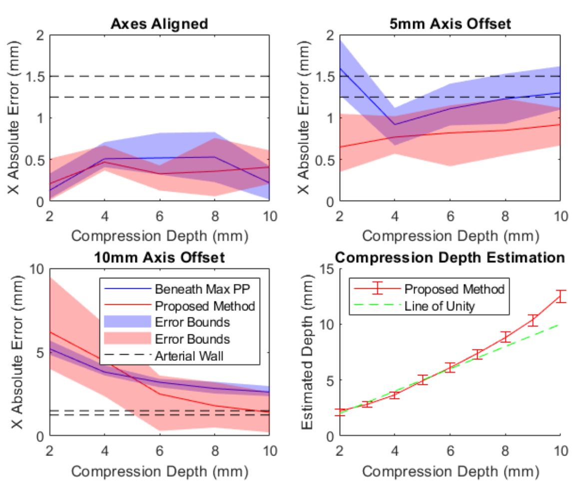

Figure 4 - X axis artery location and compression depth measurement results. Results show that proposed method is a general improvement over estimating location beneath max pulse element. Results below arterial lines indicate a likely hit, above indicates a miss, and between indicates striking the arterial wall.

Where the artery is well centered with the tactile array, both methods perform equivalently well, within an artery radius typically. As the offset increases to 5mm, the error from the previous max pulse element method exceeds the artery dimensions which would lead to missed punctures or perforation of the artery wall. The error from the proposed method is within tolerance for this offset showing the method is effective. In this situation error generally increases with compression depth, likely due to the artery moving horizontally in response to the load.

When the artery is not beneath the array, but is still detectable (10mm offset), both methods perform poorly, however the proposed method is still a general improvement over the max pulse element method. The proposed method has higher error bars than the max pulse method indicating instability. Error improves with compression depth for the proposed method as the angle between the normal and tangential vectors increases. Error improves with compression for the max pulse method as more elements become engaged allowing the max pulsing element to move towards the artery. In reality this measurement would indicate the user to move the array over the artery.

Depth measurement using gaussian fitting is effective up to approximately 6mm of compression, with errors increasing to non-useful values beyond this point. This is likely due to non-linearity in the phantom material, and 'mounding' of the material around the array.

VI. Discussion

The results for the proposed method are within an arterial inner diameter [12] whilst the artery is beneath the tactile array, which is an improvement over the max pulse element method, that often had errors outside of 1 artery diameter and this would lead to a miss or a perforation during TRA.

In the axially aligned situation, both methods perform similarly as the artery is directly beneath the array and so does not move horizontally with compression depth. Repeatability is good again because the artery doesn't move horizontally.

In the 5mm offset situation, error increase with compression due to slight artery motion horizontally. The initially poor measurement from the max pulse pressure method is caused by a lack of engaged elements, meaning the closest valid element is far from the artery.

The 10mm offset situation is of course not realistic for needle guidance as it is out of range, but was tested to see the operational range of the proposed method. The proposed method improved with compression, as the angular resolution of the tactile array improved as more elements engaged. Similarly the max pulse method improved with compression as the max pulsing element moved closer to the artery as more elements engaged, this converged onto the distance between the artery center and the edge of the array.

Given Equation 1, if the 'x' coordinate of the artery is located correctly, the proposed method should find the 'y' coordinate simply. This was not demonstrated as the competing method has no way of determining this value. Additionally, the compression of the phantom artery will drastically shift the reference location of the artery, making validation of 'y' problematic.

In relating this work to other clinical applications, the proposed method required a more severe curvature on the tactile array than that used in radial artery tactile blood pressure measurement applications [15] in order to achieve the necessary tangent and normal elements over a useful range. This BP measurement methods can be applied to this array, but not vice-versa. The depth measurement is likely not to be practical clinically due to interference from surrounding bones and non-linear tissue, however it is expected to have applications in other clinical tactile imaging applications [16].

VII. Conclusion

This paper presented a novel method for arterial localization based on the properties of a curved tactile array, validated in simple phantom materials. As the localization was within 1 arterial radius, this suggests that a reduction in failed TRA would be possible in future clinical testing. This method is to be developed into a clinically practical system providing dual functionality of needle guidance, and protecting the operator from accidental injury.

The arterial localization performance is expected to translate well into clinical testing, as accurate tactile measurements are not required for this to work, only relative measurements of the pulse pressure. This coupled with the relatively low cost of tactile sensor systems indicates that this will be a suitable needle guidance method in future following comprehensive clinical trialing.

References

[1] Y. Sandoval, M. R. Bell, and R. Gulati, 'Transradial Artery Access Complications', *Circ: Cardiovascular Interventions*, vol. 12, no. 11, p. e007386, Nov. 2019, doi: 10.1161/CIRCINTERVENTIONS.119.007386.

[2] T. Riangwiwat and J. Blankenship, 'Vascular Complications of Transradial Access for Cardiac Catheterization', *US Cardiology Review*, vol. 15, no. 4, 2021, doi: https://doi.org/10.15420/usc.2020.23.

[3] K. H. Narsinh *et al.*, 'Radial artery access for neuroendovascular procedures: safety review and complications', *J NeuroIntervent Surg*, vol. 13, no. 12, pp. 1132–1138, Dec. 2021, doi: 10.1136/neurintsurg-2021-017325.

[4] J. S. Kang *et al.*, 'Finger necrosis after accidental radial artery puncture', *Clin Exp Emerg Med*, vol. 1, no. 2, pp. 130–133, Dec. 2014, doi: 10.15441/ceem.14.045.

[5] Jamison A Harvey, Sarasa Kim , Mollie E Ireson , Rajiv Gulati , Malcolm R Bell, Steven L Moran, 'Acute Upper-Limb Complications Following Radial Artery Catheterization for Coronary Angiography', *J Hand Surg Am* ., vol. 45, no. 7, 2020, doi: 10.1016/j.jhsa.2019.11.007.

[6] Monique Tröbs, *et al.*, 'Predictors of Technical Failure in Transradial Coronary Angiography and Intervention', *Am J Cardiol.*, vol. 120, no. 9, 2017, doi: 10.1016/j.amjcard.2017.07.049.

[7] H. Krishna and A. Shroff, 'Ten Common (and Uncommon) Reasons for Unsuccessful Transradial Procedures', *ENDOVASCULAR TODAY*, vol. 17, no. 11, 2018, Accessed: Feb. 06, 2023. [Online]. Available: https://assets.bmctoday.net/evtoday/pdfs/et1118_SF2_Shroff.pdf

[8] A. G. Miller and A. J. Bardin, 'Review of Ultrasound-Guided Radial Artery Catheter Placement', *Respiratory Care*, vol. 61, no. 3, pp. 383–388, Mar. 2016, doi: 10.4187/respcare.04190.

[9] A. P. Sarvazyan and V. Egorov, 'Mechanical imaging in medical applications', in *Engineering in Medicine and Biology Society, 2009. EMBC 2009. Annual International Conference of the IEEE*, 2009, pp. 1975–1978.

[10] A. Sarvazyan, V. Egorov, J. S. Son, and C. S. Kaufman, 'Cost-effective screening for breast cancer worldwide: current state and future directions', *Breast cancer: basic and clinical research*, vol. 1, p. 91, 2008.

[11] K. Hynynen and R. M. Jones, 'Corrigendum: Image-guided ultrasound phased arrays are a disruptive technology for non-invasive therapy (2016 *Phys. Med. Biol* . **61** R206)', *Phys. Med. Biol.*, vol. 63, no. 1, p. 019501, Dec. 2017, doi: 10.1088/1361-6560/aa9a26.

[12] S. Beniwal, K. Bhargava, and S. Kausik, 'Size of distal radial and distal ulnar arteries in adults of southern Rajasthan and their implications for percutaneous coronary interventions', *Indian Heart Journal*, vol. 66, no. 5, 2014, doi: 10.1016/j.ihj.2014.08.010.

[13] W. Wahood, S. Ghozy, A. Al-Abdulghani, and D. Kallmes, 'Radial artery diameter: a comprehensive systematic review of anatomy', *Journal of NeuroInterventional Surgery*, vol. 14, no. 12, Feb. 2022, doi: http://dx.doi.org/10.1136/neurintsurg-2021-018534.

[14] D. Getachew, A. Astatkie, and K. Lemma, 'Diameter, Vessel Thickness and Angle of Bifurcation of the Radial Artery in Ethiopian Cadavers', *J Morphol Sci*, vol. 35, no. 02, pp. 129–135, Jun. 2018, doi: 10.1055/s-0038-1669905.

[15] R. Hampson, R. G. Anderson, and G. Dobie, 'Non-Invasive Radial Artery Blood Pressure Monitoring Using Error Compensated Tactile Sensors and Patient Specific Oscillometry', in *2022 44th Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC)*, Glasgow, Scotland, United Kingdom, Jul. 2022, pp. 828–831. doi: 10.1109/EMBC48229.2022.9871598.

[16] R. Hampson, G. West, and G. Dobie, 'Tactile, Orientation, and Optical Sensor Fusion for Tactile Breast Image Mosaicking', *IEEE SENSORS JOURNAL*, Jan. 2023, doi: 10.1109/JSEN.2023.3237906.