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Online Scaphoid Tracking Using a Wearable and Flexible Ultrasound Array: A First Proof of Concept

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ABSTRACT Percutaneous Scaphoid Fixation is a minimally invasive technique used to treat fractures of the scaphoid, the most fractured bone in the wrist. A significant challenge in this procedure is managing complications due to scaphoid movement due to wrist motion. This study aims to enhance the effectiveness of the intervention by introducing a novel wearable ultrasound array capable of flexible adherence and real-time tracking. By accurately monitoring scaphoid movement throughout the surgery, this innovation seeks to improve the overall success of the treatment. In previous research, a wearable transducer was designed to track the scaphoid during Percutaneous Scaphoid Fixation. In this study, ultrasound data was collected from this transducer and streamed to MATLAB, where an in-house developed algorithm employed template matching methods to track the scaphoid, specifically by identifying image segments that match a predefined template. With this method, we were able to demonstrate online processing at a frame rate of 28 Hz, which aligns with most clinical scanners, indicating the potential of this scaphoid tracking method for deployment on a clinical scanner.

INDEX TERMS Flexible ultrasound array, percutaneous scaphoid fixation, ultrasound tracking of the scaphoid.

I. INTRODUCTION

SCAPHOID fractures are the most common wrist fractures [1]. The standard treatment, Percutaneous Scaphoid Fixation (PSF), involves drilling into the scaphoid and inserting a screw to join the bone fragments. This minimally invasive procedure is typically guided by fluoroscopy. However, fluoroscopy has significant limitations, including the lack of a three-dimensional (3D) view of the wrist's intricate anatomy and the exposure of both the patient and surgeon to ionizing radiation. Consequently, computer-assisted orthopedic surgical (CAOS) systems using ultrasound imaging have been proposed to overcome these challenges in PSF. For instance, Beek et al. developed a computer-assisted approach for percutaneous scaphoid fixation that employs intraoperative ultrasound to register a preoperative CT scan with the patient and track scaphoid motion [2]. This approach involves preoperative planning and intraoperative guidance through ultrasound registration. A significant challenge in PSF surgical guidance is that the scaphoid's position relative to the wrist can shift as the hand moves. To address this issue, Beek et al. assumed that the hand would remain stationary during the PSF procedure [2]. Their work demonstrated that ultrasound can accurately identify the scaphoid's position relative to the skin surface. This result indicated that the proposed navigation system may enhance the reliability of percutaneous scaphoid fixations, potentially surpassing the accuracy of the conventional fluoroscopy-guided approach. Following that earlier study, Beek et al. extensively validated their previously proposed ultrasound-guided procedure [3]. They further evaluated the performance of their computer-assisted technique through laboratory experiments that simulated the surgical procedure using non-fractured scaphoid phantoms. The experiments demonstrated that a maximum error of 0.35 mm was sufficient to meet the strict accuracy requirements for scaphoid fixation surgery. Similarly, Chen et al. developed a surgical guidance system that utilizes both preoperative and intraoperative ultrasound, replacing the traditional use of preoperative CT and intraoperative fluoroscopy [4]. The technique involves constructing a 3D ultrasound volumetric model of the target bone's geometry, which is then registered with live intraoperative ultrasound images using a search-for-match algorithm based on mutual information. This algorithm compares the live images to each preoperative image in the database, to identify the best match. Preliminary laboratory experiments by Chen et al. demonstrated that this registration method could accurately and reliably identify the closest matching preoperative image to the live image, provided that the database contains an almost identical image. However, the authors noted that the computational complexity of the method increases with the density of the preoperative image database, as the search-and-match algorithm must compare the live image to every preoperative image, making the process computationally intensive. The authors concluded that, despite the algorithm's computational burden, their proposed system holds promise for providing interactive guidance in orthopedic surgery.

Several studies have explored ultrasound-based registration for computer-assisted PSF. Brößner et al. proposed a fully automated system that uses deep learning to segment and register 3D ultrasound images with preoperative CT models [5]. This system is designed to reduce both the time and manual interactions required during surgery, thereby enhancing workflow integration. The study's methodology involves creating a 3D model of the scaphoid bone from preoperative CT scans, which is then registered with real-time ultrasound data using a novel deep learning-based algorithm. This approach was validated through an in vitro study with 3D-printed carpal phantoms, where screw placements were successfully achieved with minimal deviations from the planned axis.

In addition to these algorithmic developments, flexible arrays have recently emerged in medical applications, leading to significant advancements in wearable ultrasound devices. Wang et al. reported a wearable ultrasound transducer array designed for direct skin application to enable continuous monitoring of central blood pressure [6]. This wearable array offers several key advantages over existing methods, including conformal-to-skin measurement, a compact design, and high accuracy. The array was applied to the skin over the left carotid, external jugular vein, and internal jugular vein to monitor the central blood pressure waveform. Pashaei et al. integrated matrices of PZT elements onto a flexible printed circuit board (PCB) to create flexible, linear transducer arrays for image-guided neural modulation [7]. These flexible arrays were designed to be bendable and were worn directly on a volunteer's neck. In operation, two arrays were utilized: an 8-element array for neuromodulation and a 64-element array for nerve imaging and localization. The ultrasound images were analyzed using a machine learning algorithm to accurately locate the nerve.

Despite promising results from previous studies on ultrasound-based surgical guidance and tracking, limitations persist in the context of PSF, especially in adapting to various hand movements. Accurate scaphoid positioning during PSF is crucial, and while ultrasound guidance has shown significant potential, most studies have relied on immobilizing the hand using splint-like structures [2], [3], [4], [5]. Also, flexible array technologies have been explored in other medical applications [6], [7], but no studies have specifically focused on wearable technologies for wrist and PSF surgery. To address these issues, we previously designed a dual linear flexible ultrasound array for real-time scaphoid tracking during PSF in a simulation study [8]. The aim of this study is to use this flexible ultrasound array for real-time tracking of the scaphoid during PSF surgery, thereby allowing a CAOS system to align a 3D model of the scaphoid to the patient. To achieve this goal, the flexible array will collect and stream ultrasound data to MATLAB, where a template matching algorithm will register the tracked scaphoid surface to a 3D model of the scaphoid bone, generated from a preoperative CT scan. The flexibility of our ultrasound array is essential for maintaining consistent acoustic coupling over the wrist's curved surface. Because the scaphoid is situated near complex anatomical structures, a conformable array ensures reliable contact with minimal gaps or air pockets at the skin–transducer interface, reducing motion artifacts and signal drop-outs. Additionally, making the array wearable enables hands-free imaging, allowing surgeons to use both hands during procedures instead of holding the array with one. To evaluate the performance of the flexible transducer array, we will compare the performance of the flexible transducer with that of a rigid handheld transducer. This paper is organized as follows: Section II provides a detailed overview of the experimental setup, the tracking algorithm, the registration algorithm, and a comparison between the wearable transducer and a handheld one. Section III presents and thoroughly discusses the results of the study. Finally, Section IV offers our conclusions.

II. METHODS

A. EXPERIMENTAL SETUP

The probe features a dual linear flexible configuration, incorporating two parallel 1D arrays within a single housing. Each array comprises 64 elements with a center frequency of 7.5 MHz and an element pitch of 1.5λ (0.30 mm). The transducer's two arrays were used sequentially in linear scan mode, each with a sub-aperture size of 16 elements, generating two parallel images. This setup enables the simultaneous acquisition of two parallel images and is driven by our ultrasound advanced open platform (ULA-OP 256). The array is securely positioned on the arm phantom (Pure Imaging Phantoms, UK) using a Velcro band for stability. Fig. 1 shows the experimental setup used in this study.

The use of the flexible array involves three stages after attachment to the subject. First, ultrasound data are collected to estimate the shape of the array using a phase coherence method [9]. This shape information is then used to update the transmit and receive delays for imaging, under the

FIGURE 1. **Setup for the experiment a) Array attached to arm phantomwith Velcro band b) Ultrasound scanning system (ULA-OP 256).**

assumption that the shape remains constant during the experiments. Subsequently, image data are streamed via USB 3.0 to MATLAB [10]. Prior to online streaming, manual selection of a region-of-interest (ROI) is performed on the images to provide an initial template for the tracking algorithm. Finally, an in-house developed algorithm tracks the scaphoid in subsequent frames.

B. TRACKING ALGORITHM

After streaming image data from the ultrasound machine to the PC, as described earlier, we manually draw a rectangle around the scaphoid bone in the first image frame. This ROI serves as the initial template for our tracking algorithm. This scaphoid tracking algorithm employs template matching [11] to locate regions in subsequent images that correspond to this predefined template. The algorithm performs normalized 2D cross-correlation between the template and each new image frame, identifying the peak in cross-correlation in order to locate the scaphoid bone. The rectangle then adjusts to encompass the scaphoid bone. To enhance stability and mitigate the impact of any damaged image frames, the template for each frame is updated as the average of the templates from the previous 20 frames. The motions imposed on the arm phantom closely resemble those performed during a PSF surgery. We mimicked these motions based on a video of the procedure. The surgery is performed on the scaphoid via the thenar eminence region of the palm, thus the array and fixation system do not interfere with the procedure.

C. REGISTRATION ALGORITHM

Once the scaphoid surface has been successfully tracked, we focus on registering a 3D bone structure of the scaphoid to a 3D point cloud created by the scaphoid's surfaces in the two tracked ultrasound images. Initially, two point clouds are generated from the tracked ultrasound images of the scaphoid's surfaces, one for each image. The data from both point clouds are then combined, and interpolation is performed on multiple planes between the two image planes to create a local estimate of the 3D structure of the scaphoid from the two ultrasound images. Subsequently, the Iterative Closest Point (ICP) [12] algorithm is applied to align the combined point cloud with the 3D model. The algorithm iteratively refines the rotation and translation to minimize the distance between the point clouds, ensuring accurate alignment.

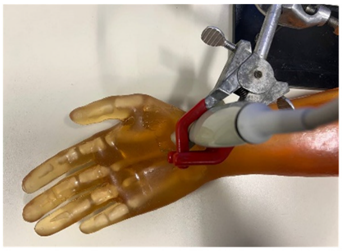

FIGURE 2. **Handheld array fixed on arm phantom.**

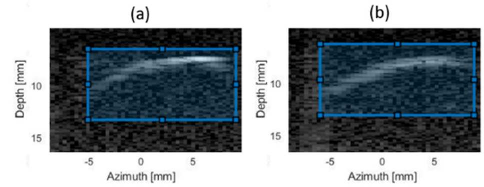

FIGURE 3. **Online images of the captured scaphoid of Arm phantom withour wearable transducer with a) first parallel array in transducer b)second parallel array in transducer.**

D. COMPARING THE PERFORMANCE OF WEARABLE ARRAY TO A HANDHELD ARRAY

To demonstrate how the flexibility and wearability of the array enhance the efficiency of scaphoid tracking, we compared its tracking performance to that of a handheld, rigid array with the same imaging parameters. The handheld array is a linear array with 128 elements, a center frequency of 7.5 MHz, and an element pitch of 1.5λ (0.30 mm). For this experiment, only the first 64 elements were used to ensure comparability with the wearable array. The array was operated with a sub-aperture size of 16 elements. The same experimental setup and motions were applied with both arrays, as depicted in Fig. 2. After comparing the tracking performance, we fed the tracked scaphoid images from the tracking algorithm into the registration algorithm to assess the impact of both arrays on the registration process. With the rigid array, unlike a flexible array, the absence of elevational information results in fewer points defining the ultrasound-based structure of the scaphoid, complicating the registration process. This limited data also slows down the registration, necessitating more iterations for the algorithm to achieve the desired error threshold.

III. RESULTS AND DISCUSSION

Fig. 3 shows the tracked scaphoid in an arm phantom using the wearable transducer and the method described in this study. In each frame, the scaphoid is enclosed within a rectangle. Fig. 4 shows the result of the registration of ultrasound-based structure and CT-based structure of scaphoid for one frame with flexible array. Using the wearable transducer, we demonstrated real-time processing at a frame rate of 28 Hz, which aligns with most clinical scanners, indicating its potential for deployment on a clinical scanner.

In comparison, the handheld transducer's rigidity prevents it from conforming to the shape of the wrist, leading to

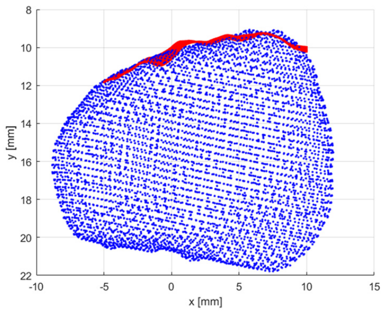

FIGURE 4. **Ultrasound-based structure (red) and CT-based structure(blue) of scaphoid registered with ICP.**

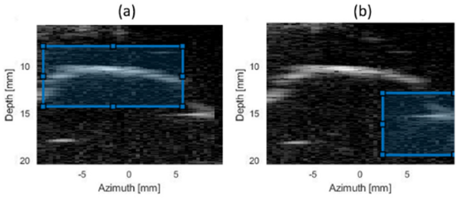

FIGURE 5. **a) handheld array capturing scaphoid b) result of an outof-plane motion that caused the handheld array to fail to capture the scaphoid in a subsequent frame.**

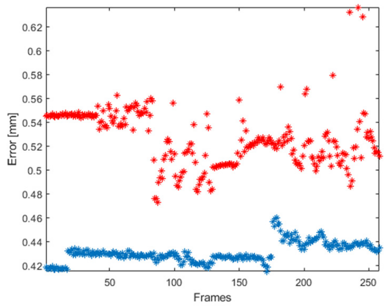

FIGURE 6. **Errors for registration of Ultrasound-based structure and CT based structure of scaphoid with rigid array (red) and flexible array(blue).**

sudden changes in the bone's image due to out-of-plane motion between consecutive frames. As a result, the scaphoid is not captured in some frames, as shown in Fig. 5(b). This unreliable capture of the scaphoid would also impact the registration process. Fig. 6 shows the registration errors for both flexible and rigid array with the same motions and same number of iterations for the ICP algorithm through different frames of the motion. As shown in Fig. 6, the rigid array produces larger errors compared to the flexible array. In addition to less accurate tracking with the rigid array, these larger errors can be attributed to the absence of elevational information. Without this information, fewer points are available to define the scaphoid's ultrasound-based structure, ultimately resulting in less precise registration.

IV. CONCLUSION

In this study, we proposed a method to track the scaphoid in real-time using a wearable, flexible ultrasound transducer. In our experiments, the PRF was approximately 2800, and with 98 transmits per frame, the resulting frame rate was about 28 Hz. This performance aligns with the capabilities of most clinical scanners, demonstrating the potential for deploying this scaphoid tracking method in a clinical setting.

Additionally, we compared our array's ability to track the scaphoid with that of a rigid, handheld array with the same imaging parameters. The handheld transducer's rigidity hinders its ability to conform to the wrist's shape, resulting in abrupt changes in the bone's image due to out-of-plane motion between consecutive frames. As a result, the scaphoid is occasionally not captured in some frames. The lack of elevational information in the rigid array, combined with the inability to handle out-of-plane motions, results in less accurate registration.

This proof-of-concept study established that real-time scaphoid tracking using the flexible array is feasible. However, the tracking algorithm was not validated due to the absence of ground truth data. Future research will focus on validating the algorithm by designing an experiment that establishes a reliable ground truth, thereby enabling the calculation of tracking errors.

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