Evaluation of a Robot's Performance for Medical 3D-Ultrasound Imaging

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Introduction

While 3D-ultrasound (3D-US) is convenient, low-cost, and offers multiple scanning options (B-mode, Doppler, etc) for stenosis quantification of lower limb vessels, 3D-US freehand tracking systems contain limitations in either requiring a constant line of sight between the transmitter and receiver, or a quality performance depending on the distance of scanning [1, 2]. Robotic systems represent promising diagnosis tools as they can control and standardize the 3D-US process for any scanning distances without requiring a constant line of sight. Some prototypes have been developed for 3D-US [3, 4, 5]. However, these systems are still under development and are mostly used to scan the carotid arteries (short rectilinear path). Moreover, their validation effort has been focusing mostly on force feedback, control and safety. Since these robotic aspects were assured throughout the manufacturing process of our prototype robot, the accuracy in its workspace remains to be evaluated for proper 3D-US reconstruction. Therefore, our objective is to evaluate the performance of the robot for the ultrasound scanning in lower limb vessels, by assessing its accuracy, and repeatability on a calibration phantom in its workspace for the positioning of a patient's leg.

Materials and Methods

The prototype medical robot developed (Fig. 1) is based on a CRS industrial robot with six degrees of freedom, a force sensor, a teach mode permitting manual learning of a "freehand" scan, and a replay mode of the manually taught path. In addition, the system can capture and store images with their registered spatial location during tracking when coupled to an US probe. The procedure to assess the accuracy of the robot is based on calibration techniques proposed earlier [6, 7, 8]. It first requires the manual teaching of the manipulator to reach a target point in a phantom specially designed to represent the geometry of a leg. The robot manipulator then replays the taught path to reach the same target point in the phantom (Fig. 1). Data is collected by recording the Cartesian's position, orientation and joint angle of the robot's wrist, also referred to as the end-effector, at the target point for teach and replay modes. Four different angulations of the end-effector for each target point were randomly selected for this evaluation. The accuracy of the robot was analyzed by comparing the average root-mean-square (RMS) error between the phantom targeted receptacle and the 3D position fitting in it. The repeatability of the replay mode was also assessed. Great care was taken to periodically calibrate the robot in its zero reference frame in order to assure a consistent accuracy. This analysis was carried out throughout the robot's workspace with designated experimental zones for randomly selected target points on the calibration phantom. In addition, a preliminary evaluation of the 3D-US system coupled to a General Electric Vivid-5 US system equipped with a 10 MHz linear probe was conducted on a vascular phantom with double stenoses (Fig. 2) of 79.5 % and 69.9 % in area reductions [9]. A linear US scan of the phantom was taught and replayed by the robot, and the images captured were segmented with a fast-marching method based on gray level statistics and gradient adapted from [10], to provide the 3D-US reconstruction of Fig. 2.

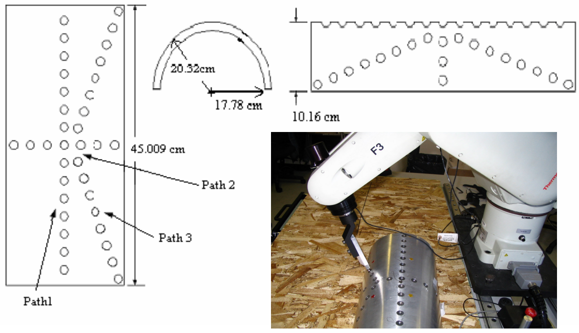

Fig. 1. Target phantom with robotic system

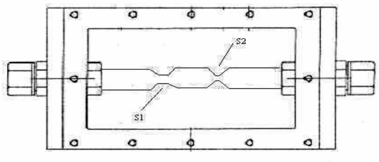

Fig. 2. Vascular phantom with two stenoses

Results

Table 1 shows the RMS errors in the 3D localization of the calibration phantom receptacles in teach and replay modes for all three paths showed in Fig. 1 in one experimental zone (The phantom was moved to define other zones). The last column presents the repeatability of the task performed by the robot (RMS values of the differences in 3D localization between teach and replay modes). As shown in Table 1, all pathways provided similar accuracy in both teach and replay modes. The repeatability as well was excellent observed for all paths. While we present the results obtained for one zone, it is to be noted that robot workspaces were obtained for other similar results.

Figure 3 shows a preliminary 3D reconstruction of the double stenosis phantom with the 3D-US system. As shown in Table 2, the percentages of area reductions of the stenoses were estimated with an error of -3.47 % and 0.87 % for the first and second stenoses.

Table 1. Summary table of the robot performance for one scanning zone

Phantom pathways (Fig. 1)	RMS errors in teach mode [mm]	RMS errors in replay mode [mm]	RMS repeatability [mm]	N (sample size)
1	0.46 ± 0.27	0.59 ± 0.30	0.18 ± 0.049	12
2	0.46 ± 0.18	0.49 ± 0.19	0.049 ± 0.0064	12
3	0.55 ± 0.25	0.60 ± 0.29	0.12 ± 0.22	16

Table 2. Summary results of the phantom 3D reconstruction

Area ratio reduction of the lumen vessel	% area reductions	3D Reconstruction	Ratio Error
Stenosis 1	79.5 %	76.03 %	3.47 %
Stenosis 2	69.9 %	70.77 %	0.87 %

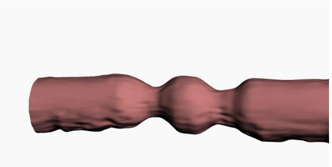

Fig. 3. Preliminary 3D reconstruction of in -vitro stenoses with the robotic scanner

Discussion

In the current study, the evaluation of a robot's performance for a medical 3D-US imaging system has been demonstrated. The results in accuracy and repeatability have provided convincing evidence in comparison to other 3D-US systems not requiring a line of sight, that the robot is an interesting alternative approach for the US scanning of lower limbs. As seen in Table 1, the mean 3D accuracy varied between 0.46 mm and 0.55 mm. As expected, the repeatability was excellent with RMS mean values below 0.18 mm. Because the orientations of the end-effector were randomly chosen in this study, these results represent the global performance for the entire robot's workspace. Other popular 3D-US systems non-requiring a line of sight have reported a precision (RMS errors) of 0.61 mm on a phantom for an electromagnetic tracking device [11]. To conclude, our study demonstrates that the robot may be used as a standard diagnosis tool for evaluating patients in any scanning zones within its reach to provide a reliable positioning accuracy. Furthermore, an adequate 3D reconstruction of the phantom with double stenoses was achieved. This gives confidence in the potential of the robot for clinical evaluation of lower limb vessels over segments going from the iliac down to the popliteal artery (≈ 50 cm).

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