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Comparison of blood sample quality and test results between robotic and manual venipuncture: a pilot study

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Abstract

Objectives: This study aimed to evaluate the feasibility of robotic venipuncture in clinical settings and compare its performance with manual venipuncture in terms of blood specimen quality and test results.

Methods: From March to April 2025, 63 participants (35 females, 28 males), aged 23–73 years, were recruited at Zoucheng People's Hospital Medical Laboratory Center. Blood samples were collected using both robotic venipuncture and manual venipuncture on April 8, 2025. Specimen quality was assessed pre-testing, and coagulation/biochemical parameters were analyzed.

Results: Robotic venipuncture demonstrated advantages in reducing venipuncture pain and achieving more consistent blood sample mixing. Compared with manual venipuncture, the robotic system enables more precise control of blood collection volume and anticoagulant ratio. Statistically significant differences ($p<0.05$) were observed in fibrinogen (Fib), prothrombin time (PT), plasminogen activity (PTA), activated partial thromboplastin time (APTT), International Normalized Ratio (INR), thrombin time (TT), potassium (K^+), lactate dehydrogenase (LDH), α-hydroxybutyrate dehydrogenase (HBDH) levels between the two methods.

Conclusions: Robotic venipuncture technology demonstrates clinical feasibility, offering more precise blood collection volumes and accurate anticoagulant-to-blood ratios compared to manual venipuncture, thereby enhancing specimen stability (Lippi G, Salvagno GL, Montagnana M, Lima-Oliveira G, Guidi GC, Favaloro EJ. Quality standards for sample collection in coagulation testing. Semin Thromb Hemost. 2012;38:565–75; Reneke J, Etzell J, Leslie S, Ng VL, Gottfried EL. Prolonged prothrombin time and activated partial thromboplastin time due to underfilled specimen tubes with 109 mmol/L (3.2 %) citrate anticoagulant. Am J Clin Pathol. 1998;109:754–7). However, challenges remain, including longer procedure times and initial user acceptance barriers.

Keywords: robotic venipuncture; automated blood collection; blood specimen quality; quality assessment; clinical laboratory automation

Introduction

Venipuncture, the standard method of obtaining blood specimens in clinical laboratories [3], is primarily performed manually by trained healthcare workers. However, manual venipuncture is associated with several limitations, including operator-dependent variability, challenges in locating suitable veins (particularly in patients with obesity, hypotension, or chronic venous conditions), and risks of hemolysis or insufficient specimen volume due to improper technique. Additionally, inconsistencies in tourniquet application and needle insertion can significantly influence laboratory test results, potentially compromising diagnostic accuracy and patient care [4–6].

Recent advancements have sought to automate the phlebotomy process to improve standardization and reduce the possible influence of human error. Robotic or semi-automated blood collection systems have been developed to enhance precision and reproducibility [7–9]. Some devices incorporate ultrasound-guided or near-infrared imaging to assist in vain detection and cannulation [10]. However, many of these systems still require partial human intervention, are limited to specific patient populations, or remain in the experimental stage. To date, there is a lack of robotic venipuncture systems capable of performing complete blood collection independently in real-world clinical environments.

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In March 2025, Zoucheng People's Hospital Laboratory Center introduced MNS R600 blood collection robot, positioning the department at the forefront of intelligent laboratory innovation. Developed by Beijing Meiners Surgical Robotics Co., Ltd., the MNS R600 is reportedly the world's first fully automated robot capable of performing the entire venipuncture and specimen collection process without manual intervention. Utilizing AI-driven machine vision, multi-wavelength vascular imaging, and multi-degree-of-freedom robotic control, this system represents a significant advancement in automated phlebotomy technology. This study aims to evaluate the feasibility, specimen quality, and user experience of the MNS R600 in a real-world hospital setting. Using a within-subject paired comparison design, we compare its performance against manual venipuncture. Our goal is to provide objective data on whether robotic systems can enhance specimen standardization, reduce human error, and improve patient comfort during blood collection.

Materials and methods

Study design and subjects

This prospective, self-controlled crossover study was conducted at the Laboratory Center of Zoucheng People's Hospital, were recruited to compare blood collection via two venipuncture methods. This study recruited a total of 63 volunteers, aged 23–73 years (35 females, 28 males). All participants (100 %) were healthy individuals who underwent annual physical examinations and had prior experience with manual blood collection, establishing a reliable baseline for subsequent comparisons. All participants were first-time users of the robotic blood collection system. Additionally, 10 % of participants self-reported varying degrees of needle phobia. Participants have been informed in advance that should robotic blood collection prove unsuccessful, manual blood collection will not be performed. Manual blood collection for this trial is divided into Groups A and B, with participants assigned numbers according to recruitment sequence: odd-numbered participants were placed in Group A and even-numbered participants in Group B. Group A blood collection is performed by a member of the blood collection team with three years' experience in the role while Group B blood collection is performed by the head of the blood collection team with over 10 years of experience. All blood sample collection procedures were performed by registered nurses holding valid Chinese nursing licenses. To ensure standardized and consistent operational procedures, all participating nurses received uniform training prior to the study commencement. Training covered the specific objectives of this study, standard phlebotomy operating procedures, the correct sequence for using different types of blood collection tubes, and the required number of inversions of the tubes. Blood specimens were collected using both methods within 5 min on April 8, 2025. For each subject, a staff member recorded the venipuncture duration and pulse pressure duration during both robotic and manual procedures. For robotic venipuncture, the duration was measured from the initial inward movement of the grasping bar to its release, while pulse pressure duration was timed from the onset of perceived pulse pressure to its cessation. For manual venipuncture, the duration spanned from the nurse's initial contact with the subject's arm to the application of the post-needle adhesive patch, with pulse pressure duration measured from tourniquet application to removal.

Following blood collection, participants completed a QR code-based questionnaire assessing their experience with both venipuncture methods. Blood samples were processed promptly: sodium citrate anticoagulated specimens were centrifuged within 30 min and analyzed within 1 h, while biochemical specimens from procoagulant tubes were centrifuged post-clotting and analyzed within the same timeframe.

Equipment and reagents

The fully automatic puncture MNS R600 blood collection robot: Beijing mainashi Surgical Robot Technology Co. Ltd (Beijing, China); The disposable venous blood sample collection containers: Hebei Xinle Medical Devices Co., Ltd. (Shijiazhuang, China); Disposable venipuncture needle 21G (0.8 × 25 mm): Tianjin Fareast medical Co., Ltd (Tianjin, China); Disposable venipuncture needle 22G (0.7 × 25 mm): Shandong Aosaite medical devices Co., Ltd (Heze, China); Japan Sysmex CP3000 automatic coagulation analyzer and supporting reagents: Sekisui Medical Co., Ltd (Longqi, Japan); Roche Cobas 8,000 automatic biochemical analysis system and supporting reagents: Roche Diagnostics, GmbH (Mannheim, Germany).

Blood collection methods

All manual and robotic venipuncture procedures (including pre-collection patient preparation, puncture site selection, disinfection area, and blood collection sequence, etc.) strictly adhere to the National Health Industry Standard WS/T 661–2020 "Specifications for Venous Blood Specimen Collection" issued by the National Health Commission of the People's Republic of China.

Manual venipuncture procedure: participants clenched their fists, and a tourniquet was applied 5–7.5 cm above the elbow. The puncture site was selected via palpation/visual inspection, sterilized in a 5-cm circular area, with povidone-iodine, and stabilized by stretching the skin 2.5–5 cm below the puncture point. A butterfly needle (22G, 0.7 × 25 mm) was inserted at a 30° angle to the elbow plane; venous entry was confirmed by blood flashback, followed by slight advancement. The needle was then connected to a vacuum tube for blood collection. Approximately 3 mL of venous blood was drawn into both the citrate anticoagulant tube and the procoagulant tube. After collection, the needle was withdrawn, and pressure was applied with an adhesive patch [11].

Robotic venipuncture

The robotic venipuncture process, as illustrated in Figure 1, begins with patient information verification by the device. The system then performs upper arm pulse pressure measurement and uses image navigation technology to identify the optimal puncture point. After elbow disinfection, the robotic arm positions the blood collection needle (21G, 0.8 × 25 mm) for precise puncture. The device automatically collects the required blood volume into vacuum tubes and thoroughly mixes it, releases the pulse pressure, swiftly retracts the needle, and applies a hemostatic patch to complete the procedure.

As shown in Figure 2, the blood collection robot utilizes three light sources (visible light and two near-infrared wavelengths) to locate blood vessels. It then employs AI-powered machine vision-a bioinformation recognition technology-to capture vascular imaging data. Using image-guided navigation control, the robot plans puncture paths tailored to blood vessels of varying orientations across different patients. Finally, multi-degree-of-freedom automated puncture technology enables precise vessel penetration and blood collection at different depths.

Assessment of subjects' experience with the two venipuncture modalities

An electronic questionnaire (hosted on Questionnaire.com) was used to collect participant feedback on their experience with two venipuncture modalities. The study involved obtaining blood samples from the same subjects within 5 min. The questionnaire was accessible at: https://www.wenjuan.com/s/UZBZJv9sOq/.

Pre-test specimen evaluation for both venipuncture modalities

Blood specimens obtained by venipuncture were divided into two groups-the robotic puncture group and the manual puncture group-for pre-test quality assessment, coagulation testing, and biochemistry analysis. Both venipuncture

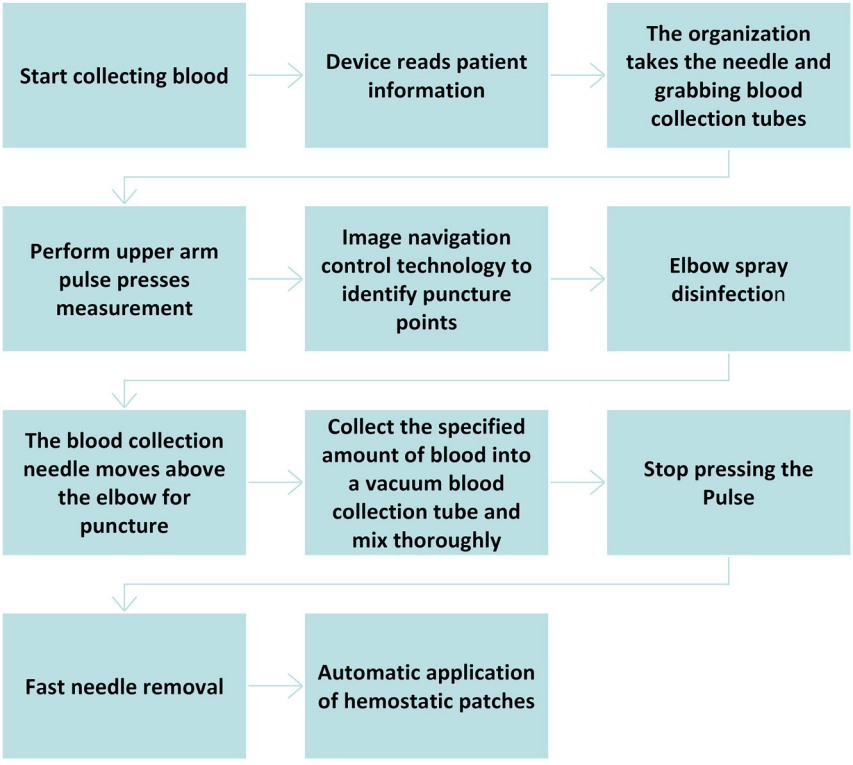

Figure 1: Robotic venipuncture blood collection method.

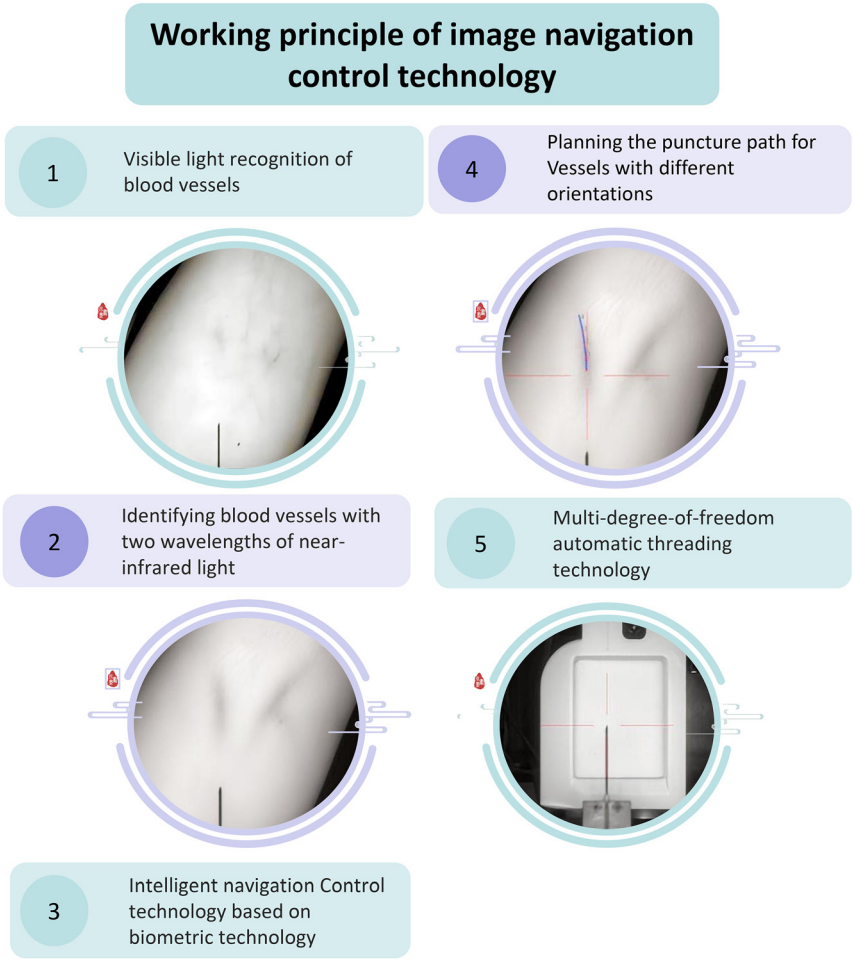

Figure 2: Diagram of the working principle of image robotic venipuncture.

procedures and subsequent laboratory testing were performed in strict compliance with the relevant industry standards issued by the Ministry of Health of the People's Republic of China.

To monitor the standardization of blood draw volume with a visual assessment method to determine whether the volume of venipuncture blood met industry standards and whether the anticoagulated blood specimens had clots visible to the naked eye. An ultra-micro electronic balance with a graduation value of 0.01 mg was used to measure the mass of blood specimens in order to assess the standardization of blood draw volume.

Blood specimen testing

The anti-citrated blood specimen was centrifuged at 2,000×*g* for 10 min under standardized conditions (room temperature) using a Nippon Sekisui CP3000 analyzer. For biochemical specimens collected in procoagulation tubes, complete clot formation was ensured prior to centrifugation at 3,000×*g* for 10 min. Testing was subsequently performed on a Roche Cobas 8,000 platform.

Comparison of anti-sodium citrate coagulation results between two venipuncture methods

After centrifuging the sodium citrate anticoagulated specimens under standardized conditions (using the same centrifuge with specified speed and time), the test results were categorized into two venipuncture methods. The differences in coagulation indices between the two venipuncture methods were then analyzed and compared.

Comparison of procoagulant tube results between two venipuncture methods

After complete coagulation and standardized centrifugation (using specified speed and time in the same centrifuge) of

blood samples collected in procoagulant tubes for biochemical testing, the results were categorized into two groups based on the venipuncture method: robotic venipuncture group and the manual venipuncture group. The biochemical indices of the two groups were then analyzed and compared to evaluate potential differences.

Statistical analysis of data

Data analysis was performed using Rimage 6.0 and IBM SPSS Statistics 27.0. For normally distributed data, paired t-tests were applied, with results expressed as mean±standard deviation. For non-normally distributed data, the Wilcoxon signed-rank test (for two related samples) was used, with results reported as median and interquartile range (IQR). Count data is expressed as frequency and percentage.

Results

Assessment of pre-test impact factors of two venipuncture modalities

The first-attempt success rate was 100 % for the manual venipuncture and 95.2 % for the robotic venipuncture (Table 1). The median puncture duration was significantly longer in the robot group (135 s [IQR 27]) than in the manual puncture (65 s [IQR 17]; p<0.001). Additionally, the robotic puncture group consistently performed six mixing cycles (gently inverting the specimen 180° and returning it to its original position counts as one mixing cycle), whereas the number of mixing cycles varied in the manual group.

Table 1 shows the average mass of blood specimens in sodium citrate anticoagulant tubes (g) and promoter of coagulation tubes (g), calculated after subtracting the empty tube weights. In both sodium citrate anticoagulant tubes [2.7 (2.6, 2.8) g vs. 2.5 (2.5, 2.6) g, p<0.001] and coagulation promoter tubes [3.3 (3.1, 3.4) g vs. 3.053 ± 0.217 g, p<0.001], the differences in average specimen mass were statistically significant.

To assess whether operator experience influenced specimen quality or analytical outcomes, manual venipuncture results from Group A (3 years of experience) and Group B (10 years of experience) were compared. As shown in Table 1, no statistically significant differences were observed between the two groups in puncture duration (69 vs. 64 s, p=0.410), pulse pressure duration (27 vs. 28 s, p=0.742), or specimen mass in either sodium citrate tubes (2.5 vs. 2.5 g, p=0.642) or coagulation promoter tubes (3.117 vs. 3.350 g, no statistical comparison applicable due to distribution characteristics).

Survey of volunteers' experiences with the two venipuncture modalities

When comparing the two venipuncture methods, 53 % of the subjects reported that robotic venipuncture was equally or more painful, whereas 89 % reported that manual venipuncture was equally or more painful than the robotic approach (Table 2). Before the trial, only 5 % of subjects were willing to actively choose robotic venipuncture, and 20 % were open to selecting it in the future. However, after experiencing both methods, the percentage of subjects willing to actively opt for robotic venipuncture increased to 27 %, and those open to choosing it next time rose to 40 %.

Table 1: Assessment of blood samples obtained by venipuncture in both modalities.

Venipuncture methods	Manual venipuncture			Robotic	p-Value
	A group	B Group	p-Value	Venipuncture	
Sodium citrate anticoagulant tube, g[b]	2.5 (2.5, 2.6)	2.5 (2.5, 2.6) 2.5 (2.5, 2.6)	0.642	2.7 (2.6, 2.8)	<0.001
Promoter of coagulation tube, g	3.117 ± 0.395	3.35 ± 0.249 3.053 ± 0.217[a]	N/A	3.3 (3.1, 3.4)[b]	<0.001
Puncture duration, s[b]	69 (57, 82)	64 (56, 72) 65 (57, 74)	0.41	135 (124, 151)	<0.001
Pulse pressure duration, s[b]	27 (24, 32)	28 (25, 30) 28 (24, 31)	0.742	45 (41.3, 49.8)	<0.001
Number of mixing times	3	4 3~4	N/A	6	N/A
1 puncture success rate	100 %	100 % 100 %	N/A	95.20 %	N/A

[a]Normally distributed data, using paired t-test and statistics are expressed as mean±standard deviation. [b]Non-normally distributed data use two related samples rank-sum test and statistics are expressed as median and interquartile range.

Table 2: Assessment of subject experience with both venipuncture modalities.

Distinguishing between the sexes	Male	Female	Aggregate	Proportions
Participant (in a clinical trial etc.)	**29**	**31**	**60**	**100 %**
Robotic venipuncture				
Left (-hand)	20	16	36	60 %
Right (-hand)	9	15	24	40 %
Degree of pain	15	17	32	53 %
Preferred blood collection method before participation	1	2	3	5 %
Preferred blood collection method after participation	12	4	16	27 %
Manual venipuncture				
Left (-hand)	9	15	24	40 %
Right (-hand)	20	16	36	60 %
Degree of pain	25	28	53	89 %
Preferred blood collection method before participation	21	24	45	75 %
Preferred blood collection method after participation	5	15	20	33 %
Depends on the situation				
Preferred blood collection method before participation	7	5	12	20 %
Preferred blood collection method after participation	12	12	24	40 %

Table 3: Evaluation of the advantages of the two venipuncture modalities by the 60 subjects with successful punctures.

Participant (in a clinical trial etc.)	Quorum	Proportions
Manual venipuncture		
Efficient communication	13	22 %
Technically skilled	7	12 %
Flexible piercing position	24	40 %
Portability	5	8 %
Short puncture time	11	18 %
Robotic venipuncture		
Operational precision	8	13 %
Less pain	22	37 %
Pulse pressure comfort	3	5 %
Standardization of puncture parameter settings	13	22 %
Avoiding needle sickness and blood	14	23 %

Table 4: Evaluation of disadvantages between two venipuncture modalities by 60 subjects with successful punctures.

Participant (in a clinical trial etc.)	Quorum	Proportions
Manual venipuncture		
Highly painful	19	32 %
Multiple puncture failures	17	28 %
Sick of needles, sick of blood	24	40 %
Robotic venipuncture		
Lack of humane communication	17	28.30 %
Risk of equipment failure	10	16.70 %
High equipment costs may lead to increased costs of blood collection	6	10 %
Poor ability to cope with complex blood vessels	27	45 %

Comparing the two puncture methods, 40 % of subjects preferred manual puncture primarily for its flexibility in positioning, while 22 % valued its efficiency in communication, and 18 % appreciated its shorter procedure time (Table 3). On the other hand, 37 % of subjects considered reduced pain the biggest advantage of robotic venipuncture, 23 % highlighted its effectiveness in preventing needle sickness and minimizing bloodshed, and 22 % favored the standardized parameter settings offered by robotic puncture.

Among the surveyed subjects, 40 % cited the inability to overcome blood- and needle-related anxiety as the primary disadvantage of manual venipuncture, while 32 % considered pain the main drawback, and 28 % feared repeated puncture attempts (Table 4). Regarding robotic venipuncture, 45 % of participants believed its key limitation was poor adaptability to complex vasculature, and 28.3 % felt it lacked humanized interaction.

Comparison of citrate anticoagulant tube test results between two venipuncture methods

As shown in Table 5, the coagulation test results from sodium citrate tubes obtained via the two venipuncture methods revealed statistically significant differences in multiple parameters. Specifically, fibrinogen (Fib), prothrombin time (PT), plasminogen activity (PTA), activated partial thromboplastin time (APTT), and the International Normalized Ratio (INR) all exhibited highly significant differences

Table 5: Differences in the results of specimens for citrate anticoagulation between the two venipuncture methods (n=60).

Measurand	Unit (of measure)	Manual venipuncture test results	Robotic venipuncture test results	t/Z	p-Value
Fibrinogen	mg/dL	2.693 ± 0.569[a]	2.77 (2.44, 3.17)[b]	6.026	<0.001
Prothrombin time[a]	s	12.585 ± 0.815	12.395 ± 0.768	6.386	<0.001
Plasminogen activity	%	99.650 ± 15.247[a]	104.6 (91.18, 110.40)[b]	5.912	<0.001
Thrombin time[a]	s	17.032 ± 0.830	16.928 ± 0.736	2.263	0.027
Activated partial thromboplastin time[a]	s	30.642 ± 2.735	30.125 ± 2.667	6.068	<0.001
International Normalized Ratio[a]	/	1.014 ± 0.082	0.997 ± 0.077	6.237	<0.001
D-dimer[b]	mg/L	0.425 (0.38, 0.52)	0.435 (0.38, 0.54)	0.278	0.781

[a]Normally distributed data, using paired t-test and statistics are expressed as mean±standard deviation. [b]Non-normally distributed data use two related samples rank-sum test and statistics are expressed as median and interquartile range.

($p<0.001$). Additionally, the thrombin time (TT) showed a significant difference ($p<0.05$).

Comparison of procoagulant tube results between two venipuncture methods

As shown in Table 6, the biochemical test results for potassium (K^+), lactate dehydrogenase (LDH), and α-hydroxybutyrate dehydrogenase (HBDH) exhibited statistically significant differences ($p<0.05$) between the two procoagulant catheterization venipuncture methods.

Discussion

This study systematically evaluated the impact of operator experience levels on blood sample quality and subsequent analytical results through meticulous design. Results indicate that despite objective differences in operator experience (senior nurses with 10 years of experience vs. junior nurses with 3 years of experience), no statistically significant differences were observed in key analytical indicators of blood samples collected by either group. This strongly demonstrates that, within the standardized operating procedures established in this study, operator experience does not constitute a significant confounding factor at the practical level among operators who have undergone comprehensive standardized training and passed qualification assessments. Of course, this study has certain limitations, such as comparing only two operators. Future research could include more operators with diverse backgrounds and experience levels to further validate the generalizability of this conclusion and continuously refine the standardized training system for sample collection.

Table 6: Differences in procoagulant biochemical specimen results between the two venipuncture methods (n=60).

Measurand	Unit (of measure)	Manual venipuncture test results	Robotic venipuncture test results	t/Z	p-Value
Total bilirubin (TBIL)[b]	μmol/L	9.5 (7.0, 12.6)	9.4 (6.9, 13.1)	0.254	0.799
Alanine aminotransferase (ALT)[b]	U/L	13.6 (9.5, 27.4)	13.8 (9.6, 27.2)	0.940	0.347
Aspartate aminotransferase (AST)[b]	U/L	18.4 (14.9, 23.3)	19.0 (15.0, 22.8)	1.686	0.092
Urea (UA)[b]	mmol/L	4.3 (3.9, 5.4)	4.4 (4.1, 5.2)	0.385	0.700
Creatinine (enzymatic) (CREA)[a]	μmol/L	64.27 ± 12.83	64.34 ± 12.31	0.240	0.081
Total cholesterol (TC)	mmol/L	4.39 ± 0.89	4.38 ± 0.88	0.820	0.416
Triglyceride (TG)[b]	mmol/L	1.0 (0.7, 1.6)	1.0 (0.7, 1.6)	1.267	0.205
Very low density lipoprotein (VLDL)[b]	mmol/L	0.45 (0.3, 0.7)	0.45 (0.3, 0.7)	0.957	0.339
Creatine kinase (CK)[b]	U/L	85.0 (73.0, 115.0)	84.0 (71.0, 116.0)	0.937	0.349
Lactate dehydrogenase (LDH)[a]	U/L	168.95 ± 24.21	164.80 ± 25.49	2.853	0.006
Alpha-hydroxybutyrate dehydrogenase (HBDH)[a]	U/L	128.64 ± 16.32	125.78 ± 18.47	2.475	0.016
Potassium (chemistry) (K)	mmol/L	4.13 (3.9, 4.3)[b]	4.220 ± 0.360[a]	2.691	0.007
Sodium (chemistry) (Na)[a]	mmol/L	140.785 ± 1.226	140.725 ± 1.366	0.721	0.474
Iron (Fe)[b]	μmol/L	18.45 (12.2, 22.9)	18.09 (12.3, 22.9)	1.719	0.086
Inorganic phosphate (P)[a]	mmol/L	1,124 ± 0.122	1.123 ± 0.118	0.155	0.877

[a]Normally distributed data; paired t-test; results expressed as mean±standard deviation. [b]Non-normally distributed data; two related samples rank-sum test; results expressed as median and interquartile range.

This study demonstrates that robot-assisted venipuncture differs substantially from manual venipuncture in terms of standardization, specimen integrity, patient experience, and analytical performance. Robotic venipuncture leverages advanced technologies such as artificial intelligence-based machine vision and image-guided navigation, along with multi-degree-of-freedom automated puncture, to achieve precise vascular access with minimal operator dependency, thereby significantly reducing procedural variability. Additionally, its controlled negative pressure mechanism – utilizing an air pump to maintain consistent aspiration-ensures gentle blood flow into the collection tube, minimizing hemolysis and improving specimen quality. The robotic puncture method provided a more standardized mixing process, as it consistently performed six mixing cycles, whereas the manual method showed noticeable variability among operators. This standardization may reduce the influence of operator-dependent factors during sample processing. COLABIOCLI guidelines for venous blood collection recommend to mix 5–10 times in total [12].

In contrast, manual venipuncture, while faster (average 65 vs. 135 s for the robotic system), is highly dependent on operator skill and experience. Rapid aspiration during manual collection can generate transient high negative pressure, potentially damaging blood cells and altering lab results. This study identified statistically significant differences between the two methods in coagulation parameters (Fib, PT, APTT, TT, INR). These discrepancies can be attributed to several factors: (1) Needle gauge differences-the robotic system uses a 21G needle (S 0.8 × 25 mm LB), whereas manual collection employs a 22G needle (0.7 × 25 mm). According to the Health Industry Standard WS/T 359 – 2024 of the People's Republic of China, needle size should be selected based on blood collection volume, patient age, and vein thickness. For adults, 19G–21G needles are recommended, while 22G–23G needles are used for newborns, children, or adults with thin veins. Robotic systems are designed specifically for adult blood collection. In routine manual venipuncture, however, 22G needles are frequently used to accommodate patients with smaller veins. Although both comply with national standards, prior studies suggest that needle size can influence platelet activation and coagulation kinetics [13, 14]. This methodological inconsistency represents a significant limiting factor. Therefore, the findings of this study – particularly the comparisons regarding coagulation parameters and hemolysis parameters and patients' pain experiences – must be interpreted with caution within the critical context of 'needle gauge inconsistency'. (2) Negative pressure control-excessive vacuum pressure in manual collection may cause hemolysis due to rapid blood impact against the tube wall [15]. The robotic system mitigates this by pre-deflating the tube and applying gradual suction, ensuring laminar flow and reducing cellular trauma. (3) Tourniquet time and mixing efficiency-prolonged tourniquet application in manual venipuncture may introduce tissue fluid, activating coagulation pathways [16]. Additionally, robotic systems ensure immediate and standardized mixing, whereas manual mixing may be delayed or inconsistent. (4) Blood volume control is critical: too much or too little blood can alter the anticoagulant-to-blood ratio (ideally 1:9). A decreased ratio may prolong APTT and PT [17–19]. According to the Health Industry Standard WS/T 359 – 2024 of the People's Republic of China, the volume ratio of sodium citrate anticoagulant to blood in sodium citrate anticoagulant blood collection tubes is 1:9. In this study,In a 3.0 mL sodium citrate anticoagulant tube, the anticoagulant volume is 0.3 mL, thus the target of anticoagulant blood collection volume is 2.7 mL. Whole blood density is approximately 1.05–1.06 g/mL.V (anticoagulant robotic) = 2.7 g/1.06 g/mL≈2.6 mL; V (anticoagulant manual) = 2.5 g/1.06 g/mL≈2.4 mL. The target of promoter blood collection volume is 3.0 mL V (promoter robotic) = 3.3 g/1.06 g/mL≈3.1 mL; V (anticoagulant manual) = 3.0 g/1.06 g/mL≈2.8 mL (Table 1). This study demonstrates that robotic venipuncture offering more precise blood collection volumes and accurate anticoagulant-to-blood ratios, thereby enhancing specimen stability. (5) Specimens should be mixed with anticoagulant immediately after collection to prevent clot formation and ensure the reliability of coagulation testing. Gentle and adequate mixing is essential to avoid hemolysis or microclots. [20–22]. Manual blood collection is subject to variability in nursing practices, which makes standardizing the intensity and frequency of mixing challenging. In contrast, robotic blood collection allows mixing intensity to be controlled through parameter settings and mixing frequency to be fixed. From one perspective, robotic blood collection is more easily standardized. In this study, the robotic system performed six standard slow-mixing cycles per tube, whereas the number of mixing cycles varied in the manual method. Statistically significant differences were observed in hemolysis-sensitive biochemical markers (K^+, LDH, HBDH). However, these results were contradictory: potassium levels were higher in the robotic venipuncture samples, suggesting increased hemolysis, while LDH and HBDH were higher in manually collected samples, indicating more hemolysis in the manual group. These inconsistent findings suggest that the differences may be influenced by pre-analytical factors – such as variability in mixing intensity or blood agitation – rather than reflecting true differences in hemolysis alone [23–25].

Although no macroscopically visible hemolysis was observed, the discrepancies in biochemical markers highlight the need for more objective monitoring. The laboratory plans to incorporate the hemolysis index as a routine quality metric to better evaluate hemolysis and improve specimen

quality. Additionally, although the robotic system currently performs six mixing cycles, COLABIOCLI guidelines recommend five gentle inversions; thus, adjusting the robotic mixing protocol to five cycles may better align with established standards and requires further evaluation.

The robotic system's precision offers distinct advantages in settings requiring high-quality specimens, such as coagulation testing and long-term health monitoring. However, its longer procedural time may limit throughput in high-volume clinics. Future iterations could incorporate rapid modes for emergency settings while maintaining accuracy for routine diagnostics.

A notable strength of robotic venipuncture is its improved patient acceptance. In this study, 89 % of participants reported pain levels comparable to or lower than manual venipuncture, attributed to high-speed puncture ("flying needle technology") [26]and precise depth control. Additionally, 23 % preferred the "invisible puncture process," reducing anxiety in needle-phobic patients. This is particularly relevant in pediatric and geriatric populations, where procedural distress can complicate blood collection.

Despite its advantages, robotic venipuncture has limitations: longer procedure times (135 vs. 65s), difficulties with complex vasculature (e.g., obese/elderly patients, 45 % user concern), and technical reliability issues (16.7 % non-user hesitancy). Future development should focus on optimizing puncture efficiency to reduce tourniquet time, incorporating AI-driven real-time vascular analysis to improve success rates across diverse patient populations, and developing hybrid human-robot workflows to balance speed with precision. Cost reduction strategies may also facilitate broader adoption in primary care. With continued refinement, robotic venipuncture can complement conventional practices to enhance pre-analytical quality and patient-centered care in modern healthcare.

In the present study, statistically significant differences were found in the results of some of the indicators of anticoagulated blood specimens and procoagulant biochemical specimens from two different venipuncture methods, but such differences were within the permissible range of bias of the results of the validation of the correctness, as required by the analytical quality criteria in the industry standards of the Ministry of Health of the People's Republic of China [27–32].

Conclusions

Robotic venipuncture represents a paradigm shift in phlebotomy, offering superior standardization, more precise blood collection volumes and accurate anticoagulant-to-blood ratios, and patient comfort. While current limitations restrict its universal application, ongoing technological refinements-particularly in AI integration and workflow optimization-will likely expand its clinical utility. As healthcare moves toward automation, robotic blood collection systems may become indispensable in ensuring diagnostic accuracy, enhancing patient experience, and reducing operator-dependent variability. Future studies should explore long-term cost-benefit analyses and large-scale validation across diverse patient populations to solidify its role in modern medicine.

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Author contributions: RW had full access to all study data and takes responsibility for the integrity of the data and the accuracy of the analysis. RW, JW and DW contributed to the study concept and experimental design. As the first author, RW drafted the manuscript, recruited volunteers, performed data analysis and interpretation, and wrote the article. RW conducted the experiments, implemented the study protocol, and collected data. WW and DW (corresponding authors) critically revised the manuscript for important intellectual content and improved the logical flow of the text. All authors have accepted responsibility for the entire content of this manuscript and approved its submission.

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