Design and development of robotic system for precise vascular access and autonomous veinpuncture

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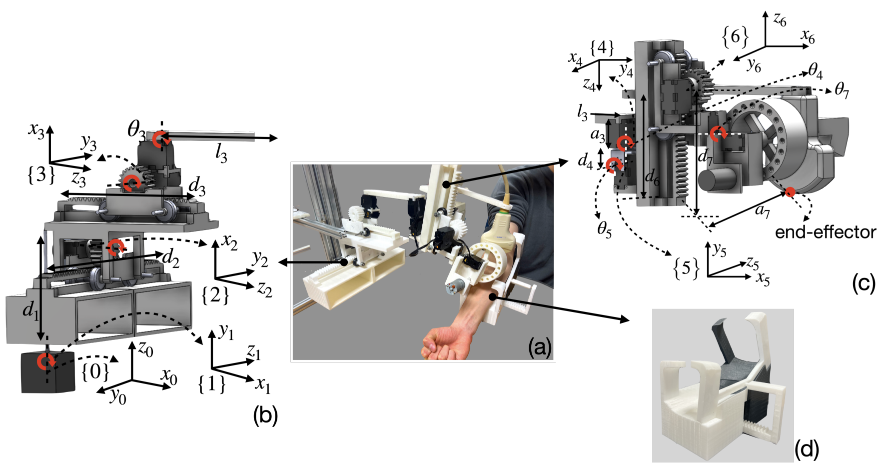
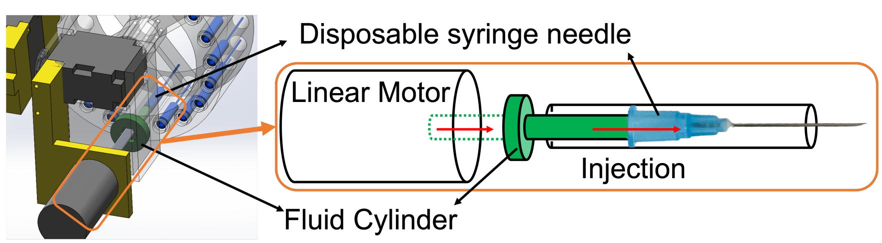
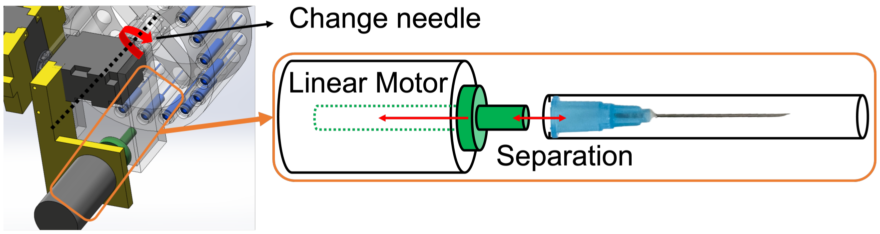
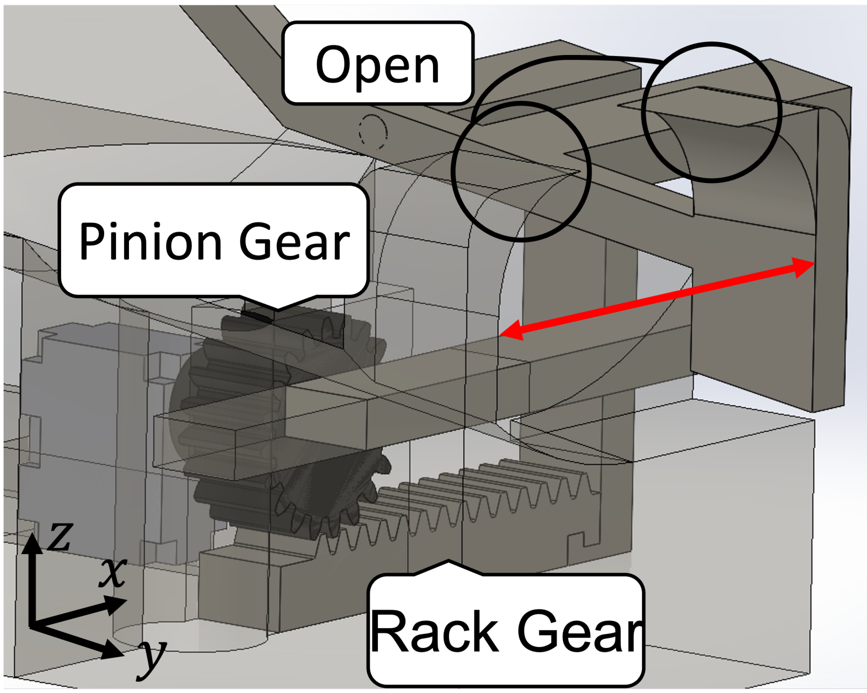
Abstract

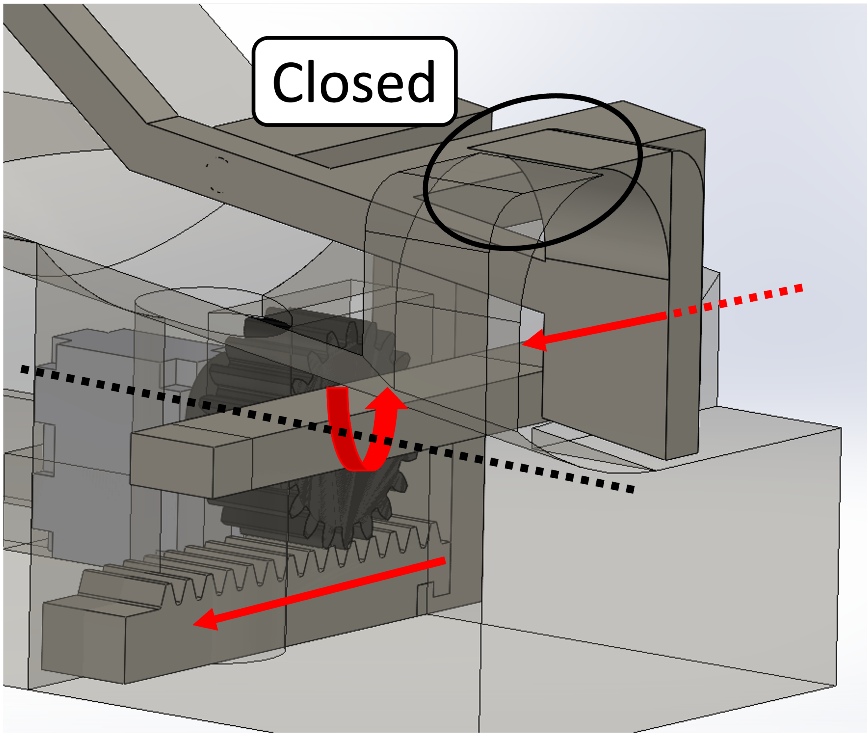
The medical robot systems have the effect of reducing the work load and preventing accidents by supporting task that are difficult for inexperienced medical practitioners. Recently, research on automated blood collection and injection robotic system has been increasing, but work is still necessary such as replacing needle tips, setting tourniquet and fixing the patient's arm. In this letter, we propose an intelligent intravenous injection robot without having to see the medical workers face-to-face. We design a revolving system for automatic needle replacement and an arm holder for vessel fixation. Finally, we experiment positioning the needle at the target point by position control based on mathematical modeling and velocity kinematics.

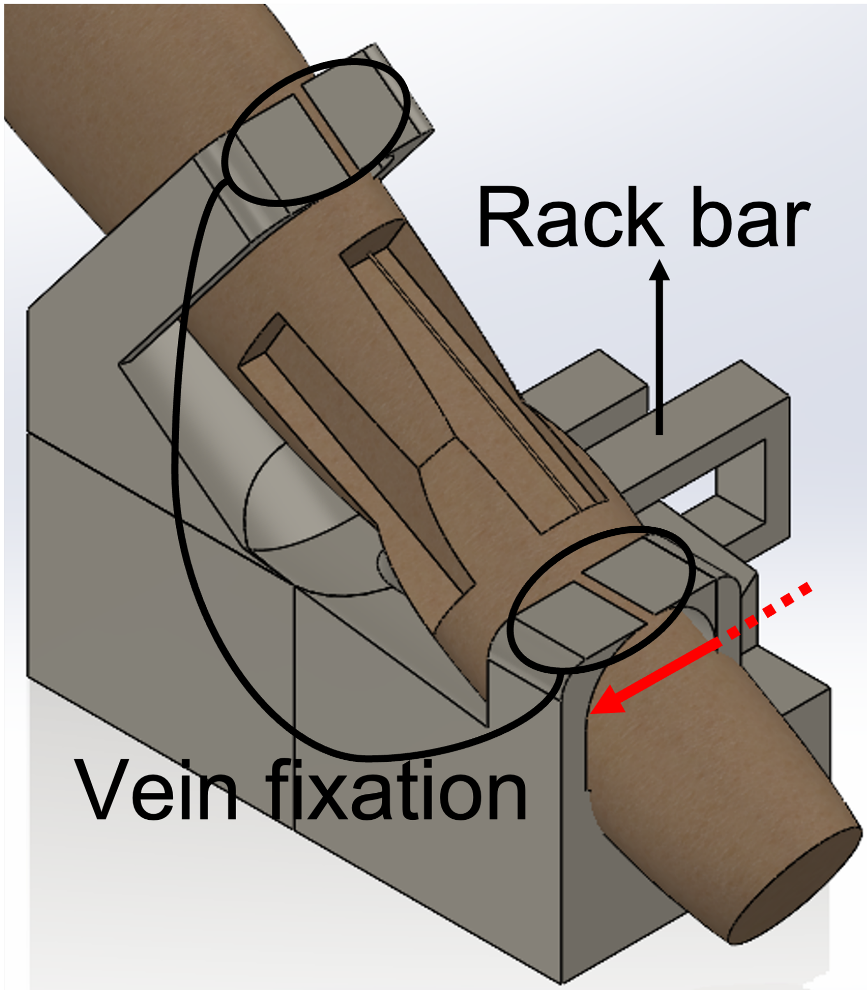


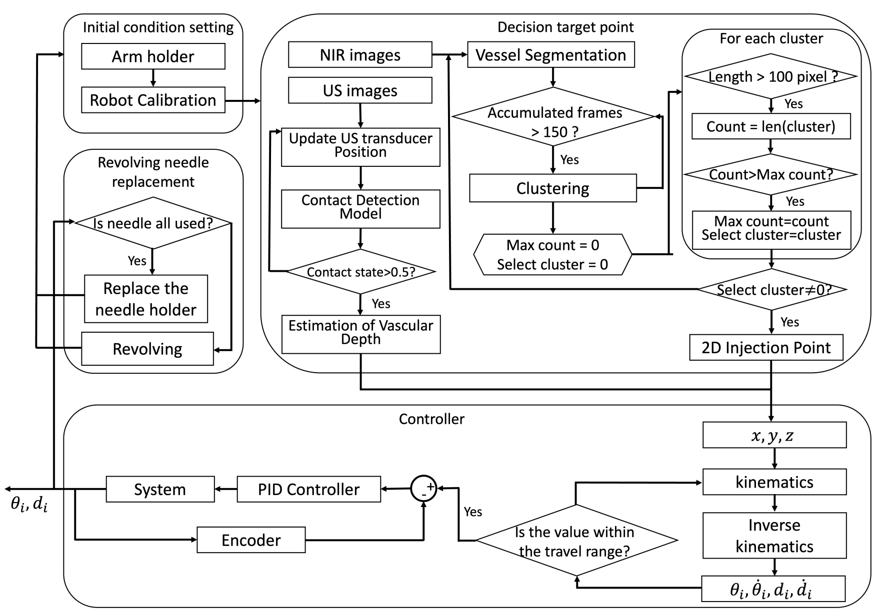


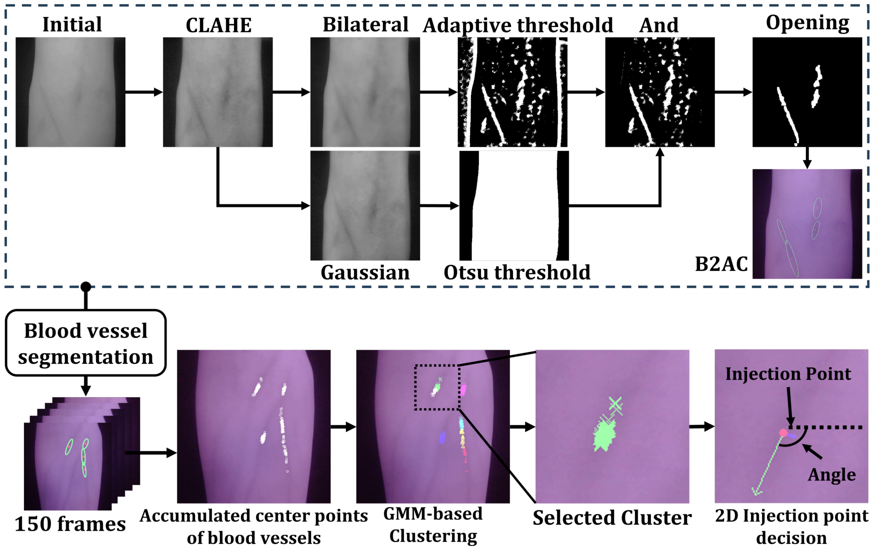

Change needle
Linear Motor
Separation

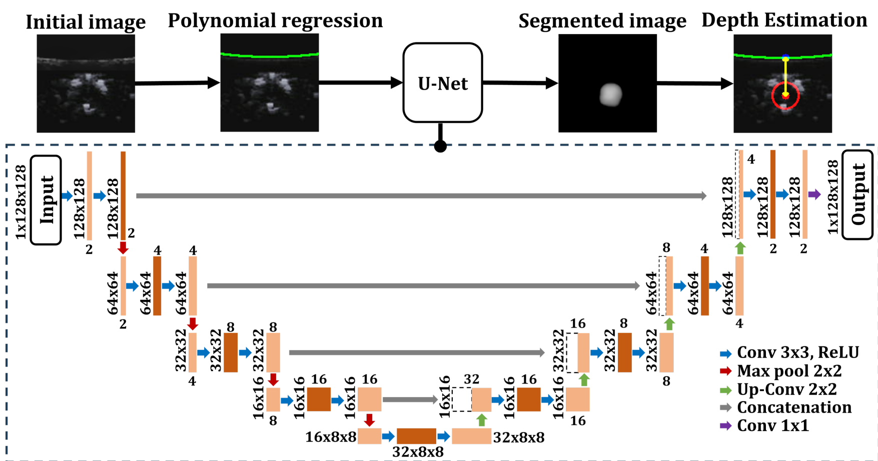

Open
Pinion Gear
Rack Gear
z
x
y

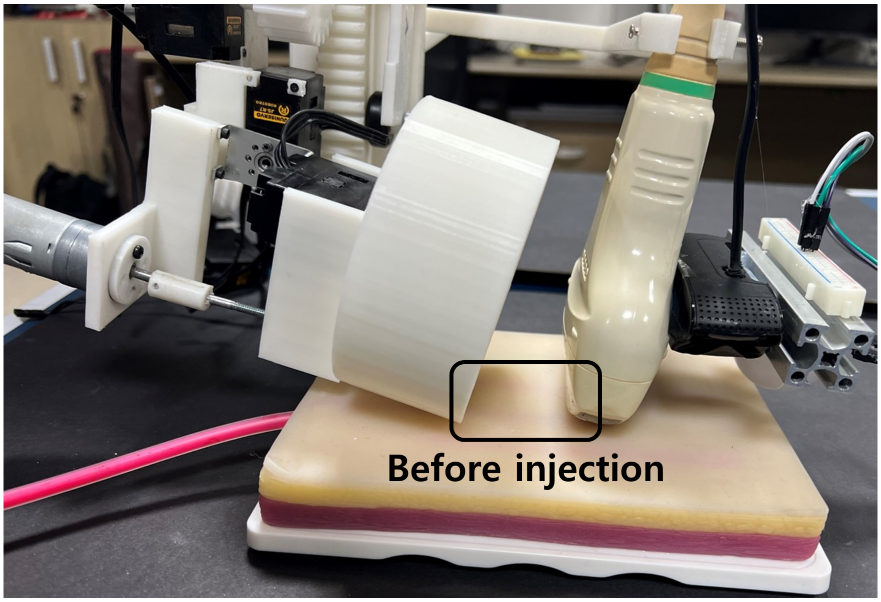

Closed

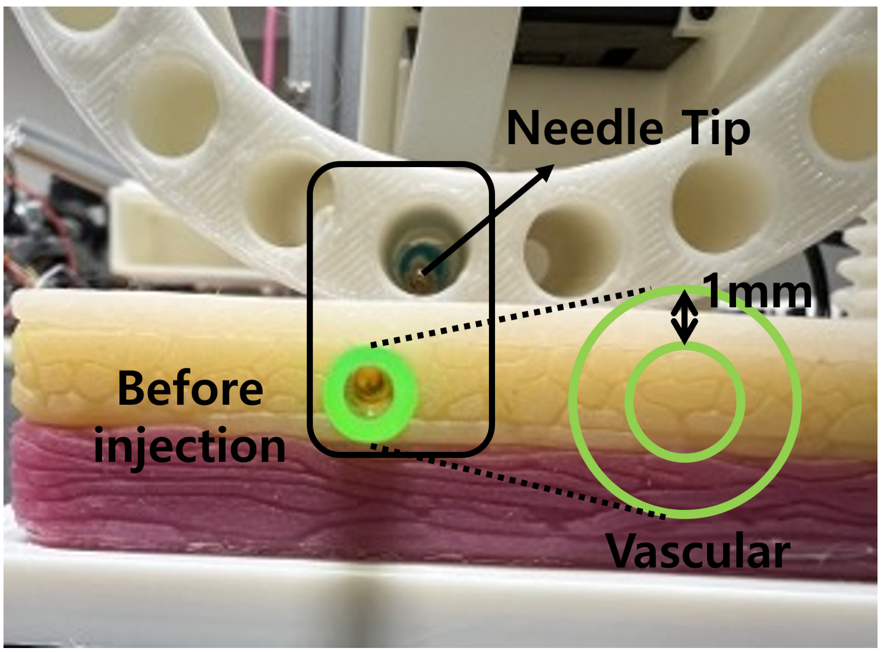

Rack bar
Vein fixation

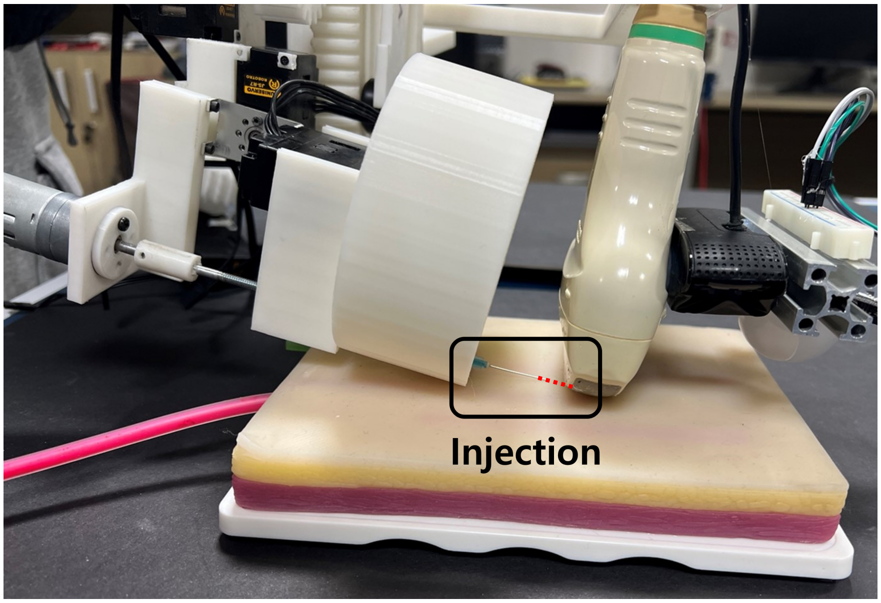

Initial condition setting
Arm holder
Robot Calibration
Revolving needle replacement
Is needle all used?
Yes
Replace the needle holder
Revolving
Decision target point
NIR images
US images
Update US transducer Position
Contact Detection Model
Contact state>0.5?
Yes
Estimation of Vascular Depth
Vessel Segmentation
Accumulated frames > 150 ?
Yes
Clustering
Max count = 0
Select cluster = 0
For each cluster
Length > 100 pixel ?
Yes
Count = len(cluster)
Count>Max count?
Yes
Max count=count
Select cluster=cluster
Select cluster≠0?
Yes
2D Injection Point
Controller
x, y, z
kinematics
Inverse kinematics
$\theta_i, \dot{\theta}_i, d_i, \dot{d}_i$
Is the value within the travel range?
Yes
PID Controller
System
Encoder
θ_i, d_i

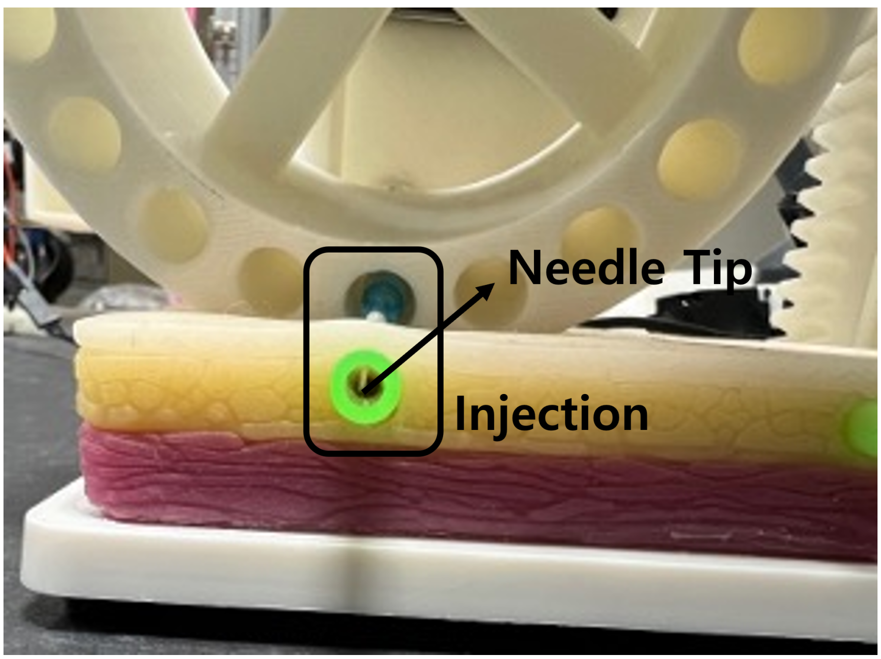

Initial
CLAHE
Bilateral
Adaptive threshold
And
Opening
Gaussian
Otsu threshold
B2AC
Blood vessel segmentation
150 frames
Accumulated center points of blood vessels
GMM-based Clustering
Selected Cluster
Injection Point
Angle
2D Injection point decision

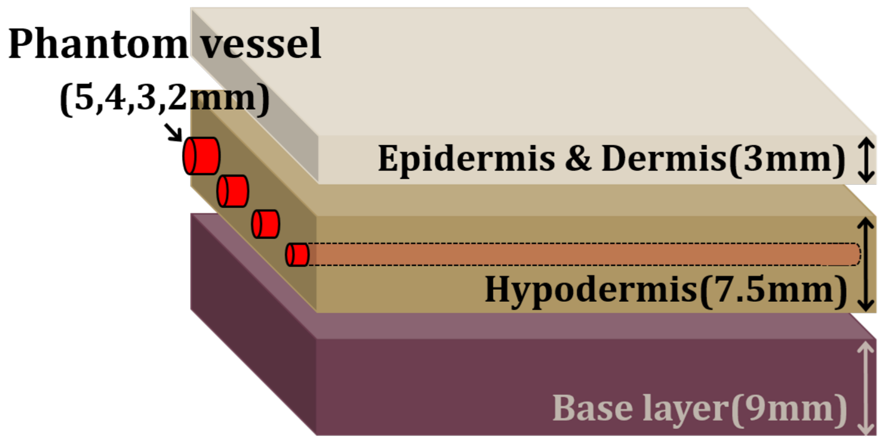

Initial image
Polynomial regression
U-Net
Segmented image
Depth Estimation
Input
Output
1x128x128
128x128
64x64
32x32
16x16
16x8x8
32x8x8
Conv 3x3, ReLU
Max pool 2x2
Up-Conv 2x2
Concatenation
Conv 1x1

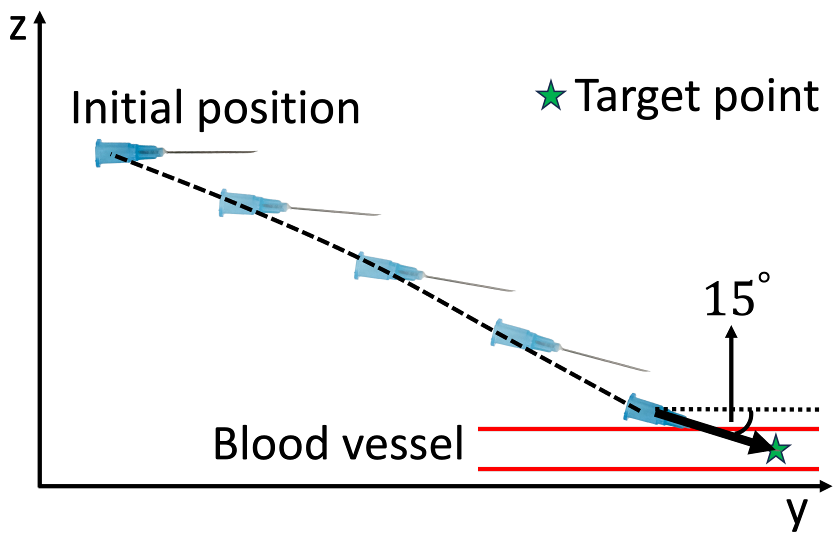

Before injection

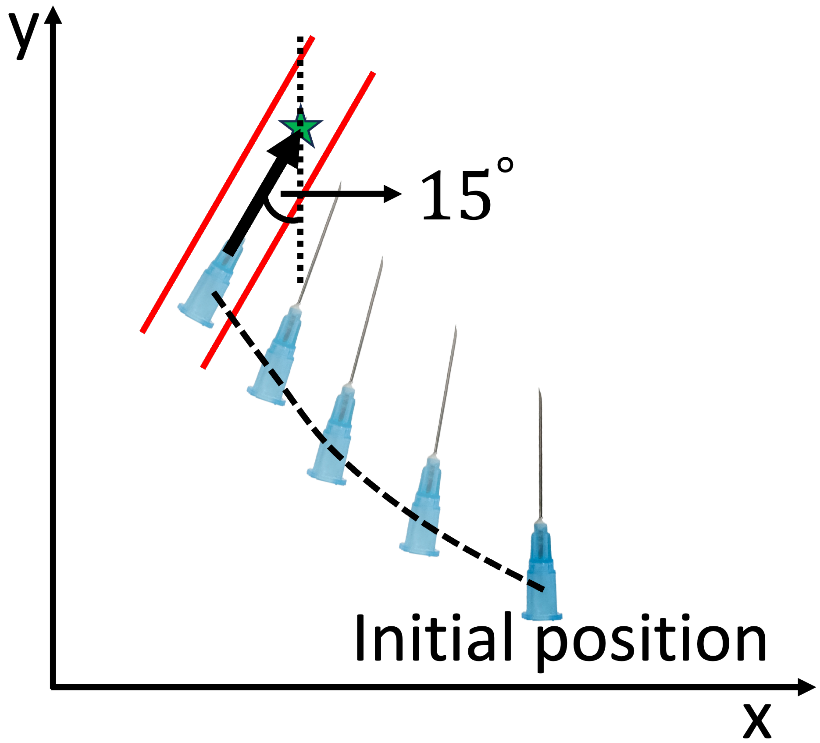

Needle Tip
1mm
Before injection
Vascular

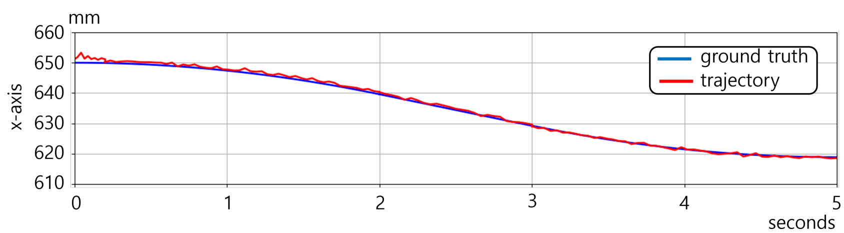

Injection

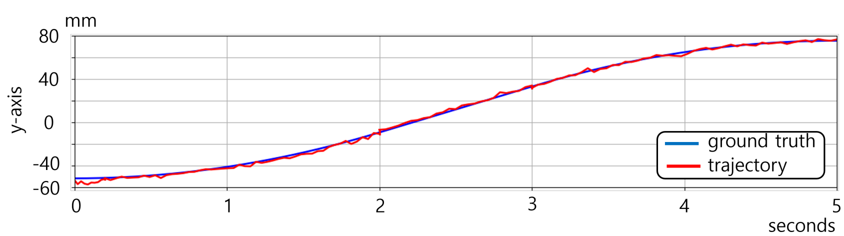

Needle Tip
Injection

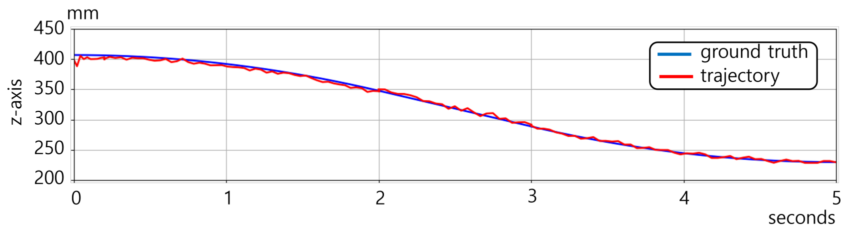

Phantom vessel
(5,4,3,2mm)
Epidermis & Dermis(3mm)
Hypodermis(7.5mm)
Base layer(9mm)

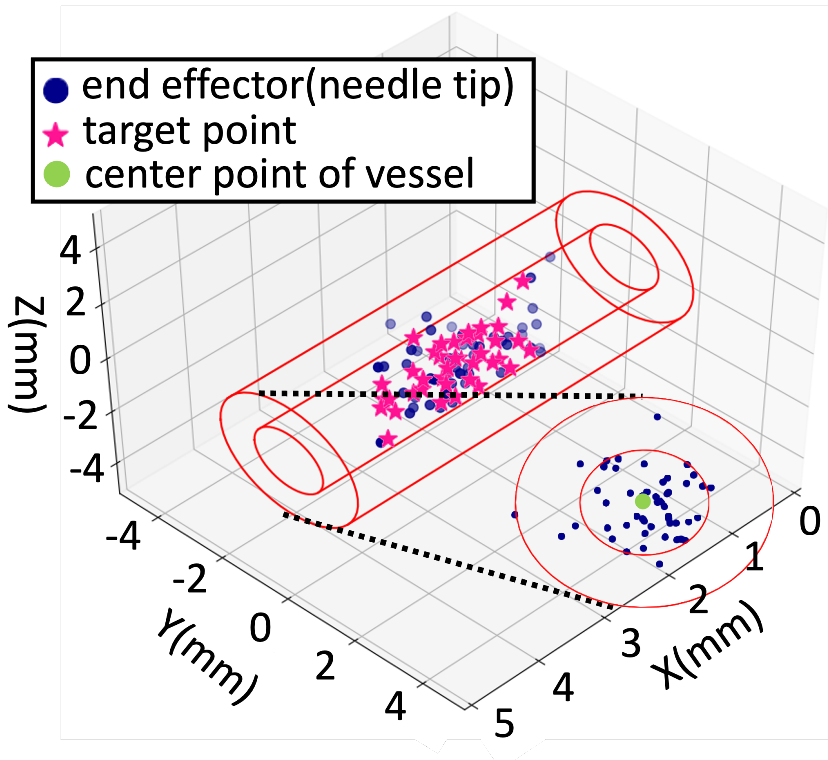

z
Initial position
Target point
15°
Blood vessel
y

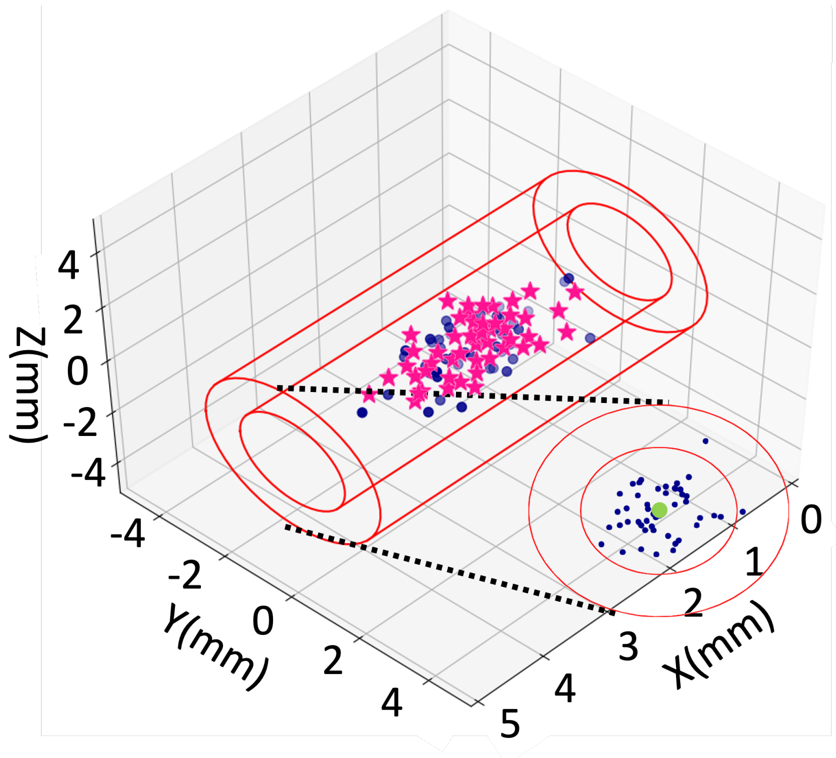

y
15°
Initial position
x

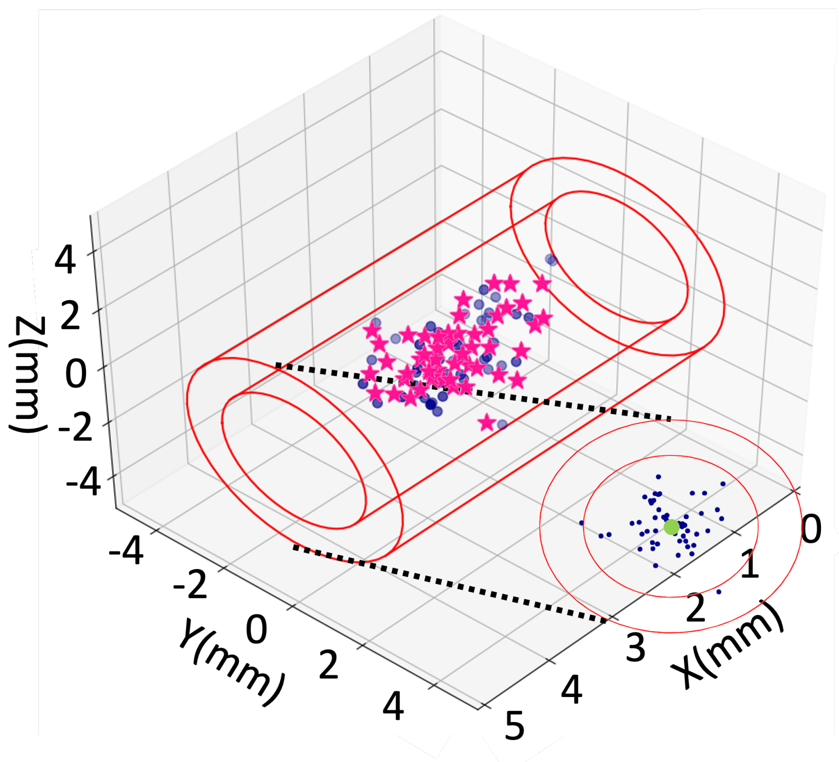

mm
660
650
640
630
620
610
x-axis
0
1
2
3
4
5
seconds
ground truth
trajectory

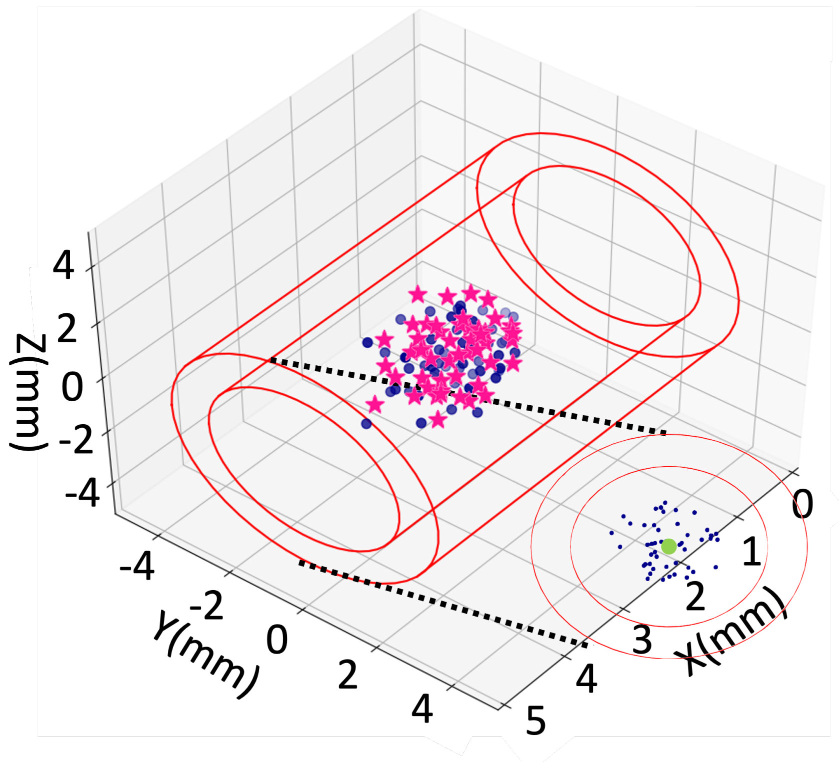

mm
80
40
0
-40
-60
y-axis
0
1
2
3
4
5
seconds
ground truth
trajectory

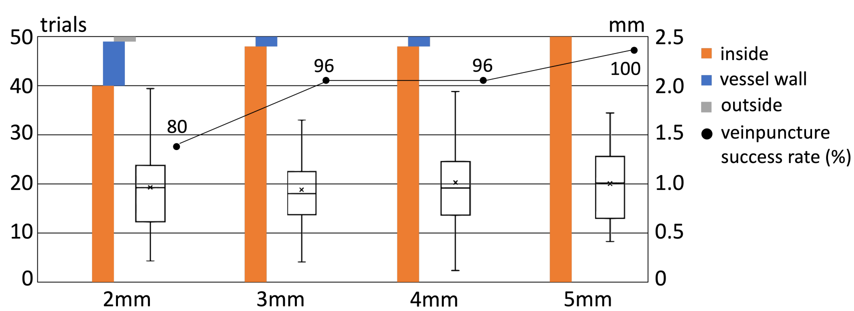

mm
450
400
350
300
250
200
z-axis
0
1
2
3
4
5
seconds
ground truth
trajectory


end effector(needle tip)
target point
center point of vessel
Z(mm)
4
2
0
-2
-4
Y(mm)
-4
-2
0
2
4
X(mm)
0
1
2
3
4
5


Z(mm)
4
2
0
-2
-4
Y(mm)
-4
-2
0
2
4
X(mm)
0
1
2
3
4
5


Z(mm)
4
2
0
-2
-4
Y(mm)
-4
-2
0
2
4
X(mm)
0
1
2
3
4
5


Z(mm)
Y(mm)
X(mm)


trials
mm
80
96
96
100
2mm
3mm
4mm
5mm
inside
vessel wall
outside
veinpuncture success rate (%)

Design and development of robotic system for precise vascular access and autonomous veinpuncture

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Introduction: Robotic systems are being intervene such as surgery and endoscopy replace medical workers through sensors and cameras, and support stable sugery through master-slave system structures such as Da Vinci and Zeus robots[1][2]. The demands for these medical robot systems are also increasing in the field of nursing work[3][4]. In particular, inexperienced medical practitioner cause veinpuncture accidents because each patient has different blood vessel thickness, depth, direction, and skin layer thickness[5][6][7]. Blood collection and injection robots have reduced needlestick injuries and prevalence, but tasks such as needle replacement, vascular fixation, and setting tourniquet still require intervention by healthcare workers[8][9][10][11]. Therefore, this letter proposes an Intelligent Intravenous Injection Robot (IVIR) system that injection or blood collection without having to see the medical workers face-to-face. We design a system that replaces the needle used through a revolving needle replacement system with a new needle, and an arm fixing unit to fix the target point. We also discuss the stability of IVIR systems through position control.

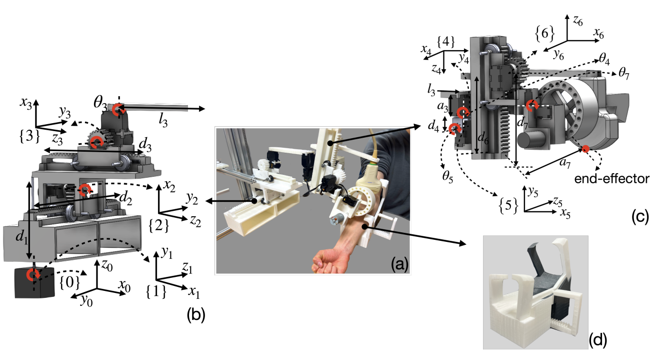


Fig 1 *IVIR prototype and coordinate system setting. (a) the prototype of the entire IVIR, (b) vein control unit, (c) vein injection unit, and (d) arm holder.*

Device Design: As shown in Fig 1(b), the vein control unit consists of gantry joints to locate the scanning target point through near-infrared (NIR) camera and ultrasonic(US) transducer. d_1 controls the depth of the patient's arm blood vessels, d_2 controls the longitudinal direction, and d_3 controls the lateral direction.

As shown in Fig 1(c), the vein injection unit consists of a gantry and Selective Compliance Articulated Robot Arm (SCARA) joint to insert the injection needle into the target blood vessel. θ_4 is controlled to align the insertion direction of the injection needle with the direction of the blood vessel, and θ_5 is controlled to move along the curved surface of the patient's arm. In addition, the revolving needle replacement system has a structure in which an needle is mounted on a needle holder and linear motor and cylinder are combined in a direction parallel to the injection needle an shown in Fig 2. The cylinder and needle are attached and separated by linear motion of the linear motor, and the revolving needle holder rotates to replace the used needle with a new needle.

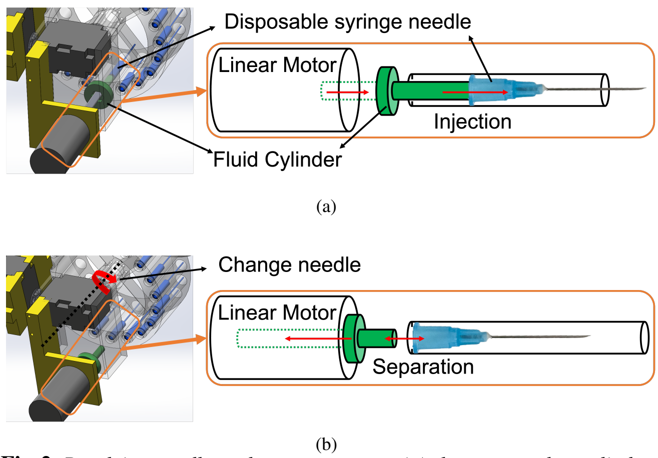


Fig 2 *Revolving needle replacement system. (a) the process that cylinder combined with the disposable syringe needle, and (b) the separated.*

As shown in Fig 1(d) and Fig 3, the arm fixing unit is designed to move the contact attachments to sides of the arm holder through the gear structure of the rack and pinion to fix the patient's arm and elbow.

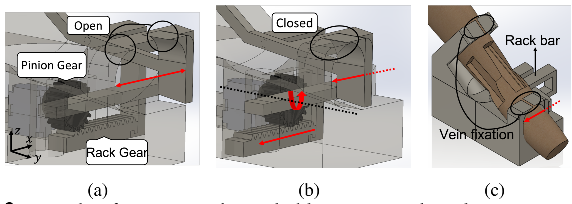


Fig 3 *Vascular fixing unit of arm holder using rack and pinion gear. (a) before fixing the patient's arm, (b) and (c) is after that.*

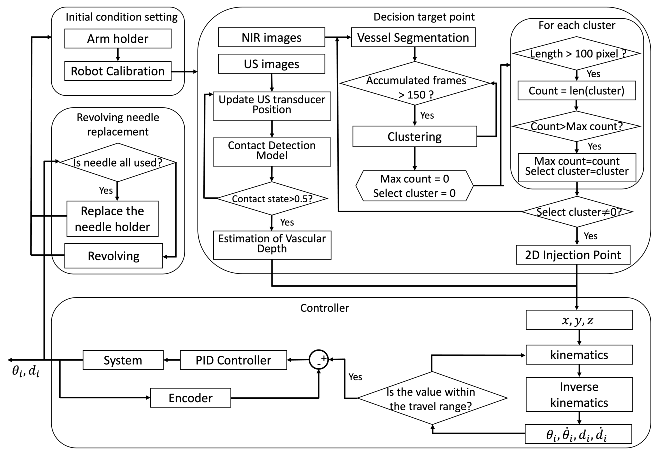


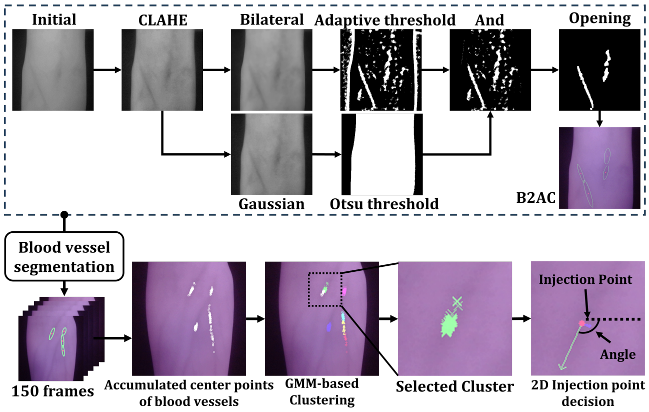
Fig 4 *IVIR system architecture*

System Design: As shown in Fig 4, injection process of IVIR consists of initial condition setting and target points decision, PID-based injection needle position control, and injection needle replacement.

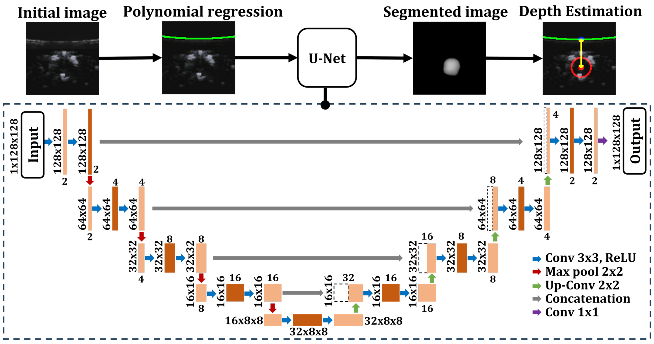
The initial condition setting fixes the patient's arm through arm holder, and each joint of the IVIR through calibration to the default position.

As shown in Fig 5, The target point for precise intravenous injection is determined using two vision systems: NIR imaging and US imaging. The clustering method is applied to accumulated frames in order to select an appropriate 2D injection point in NIR imaging. For the purpose of estimating a vascular depth in a cross-sectional view of vessel, an U-net is used. More detail contents can be referred in [12].

The kinematics represents the orthogonal coordinate space as a joint variable based on velocity kinematics (1), (2). θ_3 and θ_7 are



(a)



(b)

Fig 5 *Flowchart of the injection point determination algorithm. (a) the GMM-based 2D injection point determination; (b) the U-Net-based estimating the vascular depth.*

fixed variables that maintain 90° and 15° during the injection process, respectively. $q = [x, y, z]^T$ is a coordinate variable, $u = [d_1, d_2, d_3, \theta_4, \theta_5, d_6]^T$ is a joint variable, T is a homogeneous transform, and J is a jacobian matrix.

$$T_i = {}^0T_1 \cdot {}^1T_2 \cdots {}^{i-1}T_i \tag{1}$$

$$\dot{q} = J(u) \cdot \dot{u} \tag{2}$$

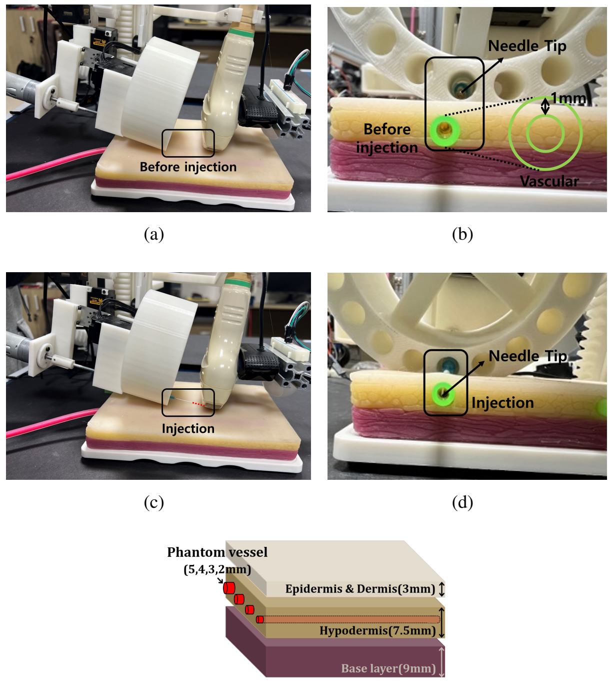
To represent the orthogonal coordinates derived by the decision target point as joint space, equation (2) is converted as (3) through inverse velocity kinematics using pseudo-inverse matrix.

$$\dot{u} = J^T(u)\left(J(u) \cdot J^T(u)\right)^{-1} \cdot \dot{q} \tag{3}$$

Revolving needle replacement reloads the used needle with a new needle after the injection process. If all new needles are used in the needle holder, the IVIR system resumes after a medical workers replace the needle holder.

Experiment: As shown in Fig 6, the target point of IVIR system control is a skin model for experimental injections, which is $180mm$ wide, $115mm$ long, and $19.5mm$ deep, and the material is food-grade silicone. The vascular tube is located in the subcutaneous tissue layer, and a total of four tubes with an inner diameter ranging from $2mm$ to $5mm$ are used to make blood vessels of various shapes signifying different patients. The thickness of the blood vessels is designed to be $1mm$.

To evaluate the precise positioning of the injection needle, the robot is repeatedly commanded to move to the same target point, measuring the repeatability in the actual position. Repeatability is measured using digital vernier calipers with a resolution of $0.01mm$, and Table 1 is the result of repeating 50 times at each target point. For each target point, the x and y-axis errors were measured to be less than $1mm$, but the z-axis errors caused a large error of 2mm or more. This is because a backlash error occurs in the rack and pinion gear of the θ_6 by the load of the vein injection unit. Therefore, the IVIR system was confirmed to be suitable for blood vessels of $3mm$ or more.



(a) (b) (c) (d) (e)

Fig 6 *Experimental environments of blood vessel injection and details. (a) and (b) the sides and cross-sections of the skin before the injection; (c) and (d) after inserting the needle respectively. (e) the structure of the artificial skin layers and sample veins.*

Table 1. Repeatability of IVIR. x, y, z is target point coordinates, e_x, e_y, e_z is error of each axis, and $3D - distance$ is euclidian distance error.

Target Point (mm)			**Error** (mm)			
x	y	z	e_x	e_y	ez	$3D - distance$
340	0	120	±0.51	±0.47	±2.12	±2.26
390	0	120	±0.96	±0.52	±2.28	±2.46
340	50	120	±0.68	±0.72	±2.06	±2.53
340	0	70	±0.55	±0.62	±2.57	±2.61

The experiment of positioning the end-effector of IVIR from the initial position to the target point is shown in Fig 7. The tracking error between the end-effector and ground truth before 0.3 seconds was up to 20 mm, but the tracking error after 0.3 seconds converged to less than 7 mm through the PID control loop. By 4 seconds, the tracking error was reduced by 20%, but there was still an error of more than $4mm$. However, after 5 seconds, the tracking error remained below $2.7mm$. Therefore, it was confirmed that the position control of the IVIR system takes more than 5 seconds.

To evaluate the veinpuncture accuracy, an injection needle is inserted into the target injection point determined through the decision target point algorithm as shown in Fig 8. The result of positioning the needle in a blood vessel with an inner diameter of $2mm$ showed a low success rate of 80% because the repeatability of IVIR is about 2-$3mm$. However, the result of veinpuncture with an inner diameter of more than $3mm$ showed an average success rate of 97.3%. Most of the 2.7% failures were caused by a slippery skin layer of food-grade silicone surrounding the outer wall of the blood vessel, so the needle showed a result of positioning on the wall of the blood vessel.

Conclusion: In this letter, we proposed an intelligent intravenous injection robot (IVIR) system that reduces the workload of injection or blood collection by medical practitioners through the revolving system to replacement of needles, and vascular fixing unit. Additionally, we proposed a system to insert injection needles at target points through veloc-

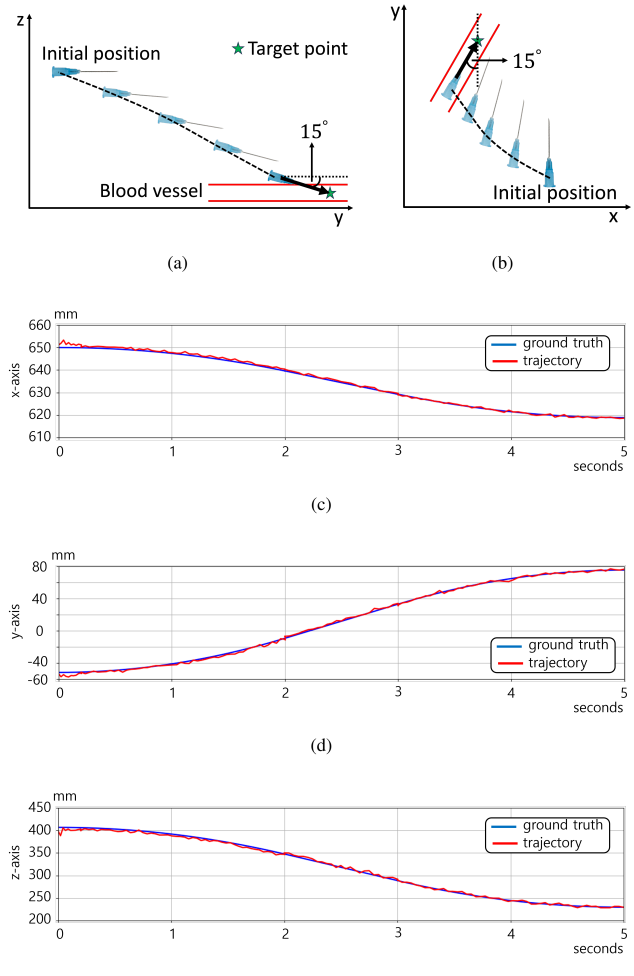


Fig 7 *The result of desired and actual positions of end-effector. (a) and (b) shows the needle located at the target point from the initial position. (c),(d), and (e) are graph of x-axis, y-axis, and z-axis based on the world coordinate system, respectively.*

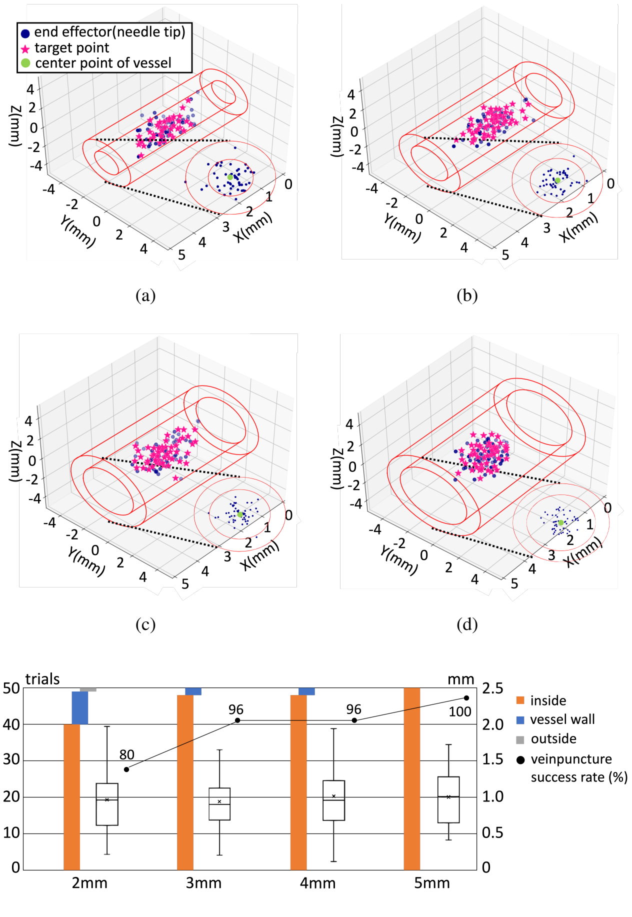


Fig 8 *Results of positioning the needle at the target injection point determined 50 times in a blood vessel with different inner diameters respectively. (a), (b), (c), and (d) are 3D and cross-sectional graphs that veinpuncture at the target injection point of vascular with an inner diameter of 2, 3, 4, and 5mm, respectively. (e) the box graph of the absolute distance error between the target injection point and the injection needle; the bar graph is the result that the needle is located inside, on the wall, and on the outside of the vascular, and line graph is the success rate of veinpuncture.*

ity kinematics using Jacobian, and PID control. The experimental results showed that IVIR was suitable for vascular of $3mm$ or more because the repeatability of IVIR was measured to be less than $3mm$. In addition, IVIR system showed a 97.3% success rate in the experiment of veinpuncture in vascular of $3mm$ to $5mm$.

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Conflict of interest: The authors declare no conflicts of interest.

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