Respiratory Motion Compensation in Robotic Spinal Osteotomy

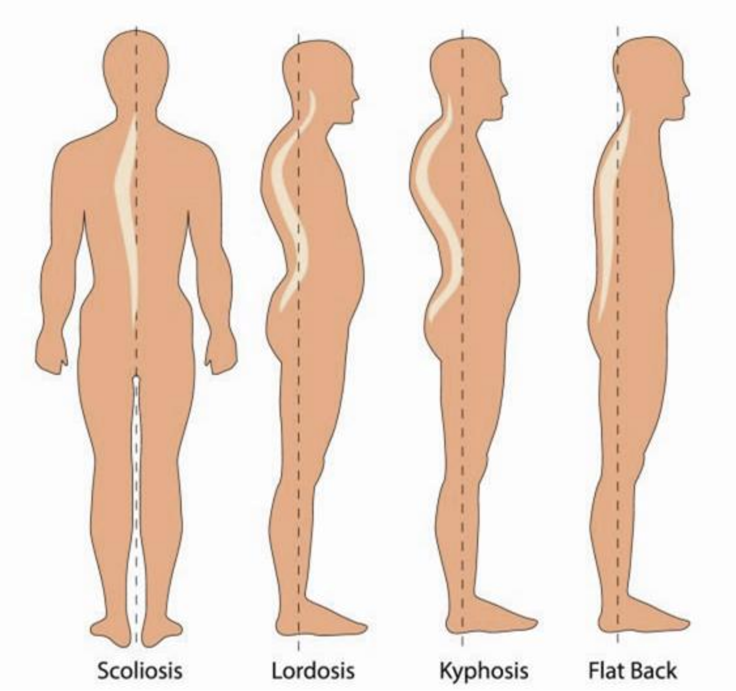
Candidate: **Livia Fabiano**

Advisor: **Prof. Elena De Momi**
Co-Advisor: **Lorenzo Casadio, Elisa Iovene**

Master of Science in Biomedical Engineering – Ingegneria Biomedica
April 3rd 2025

Academic Year 2023-2024

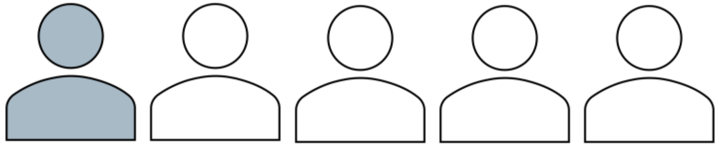
Clinical Problem



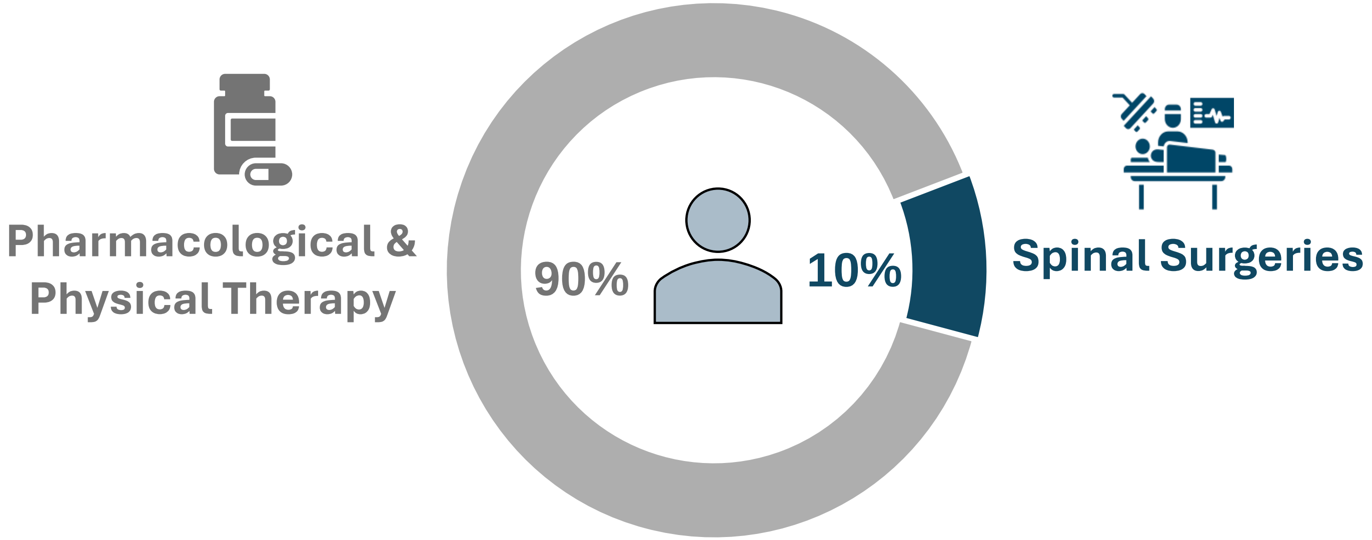
"**Spinal deformity** is **defined** as the spinal curvature or alignment that deviates from the normal limits" [1]

Spinal deformities incidence in global population

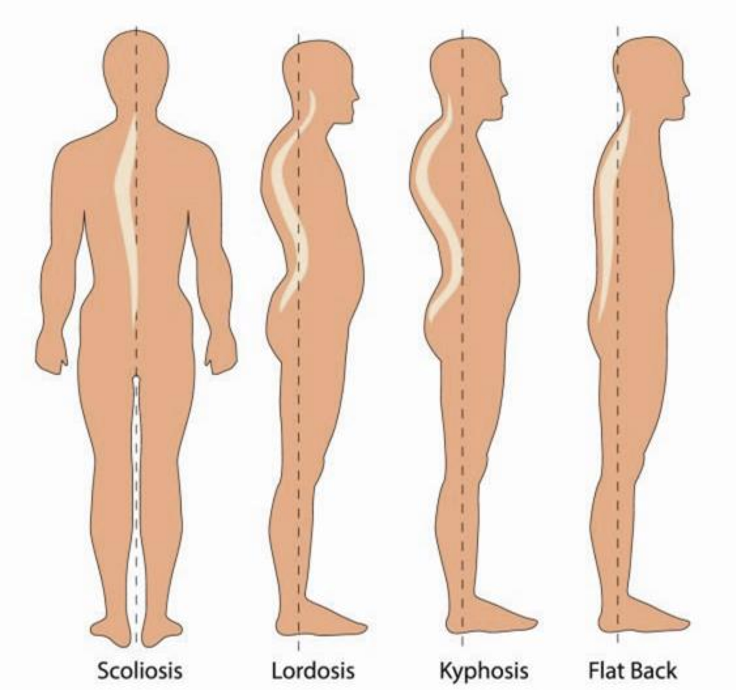
Globally, about **1 out of 5** people suffer from spinal deformities [2]



Solution [2]



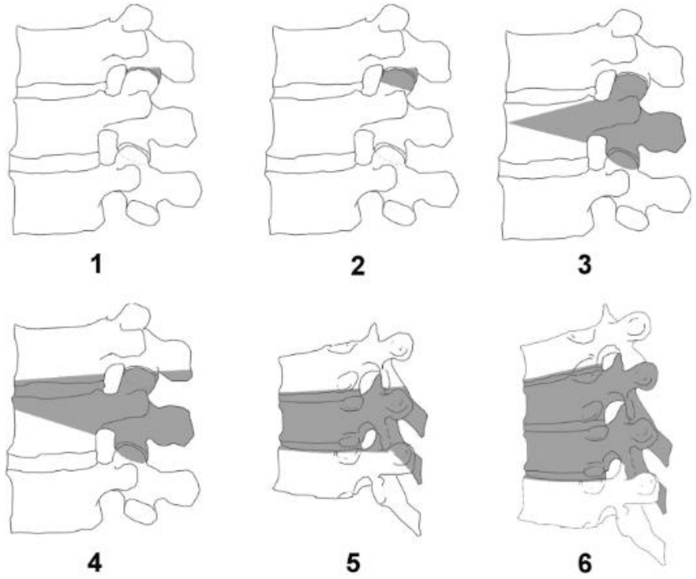
Clinical Problem



"**Spinal deformity** is **defined** as the spinal curvature or alignment that deviates from the normal limits" [1]

Spinal Surgeries

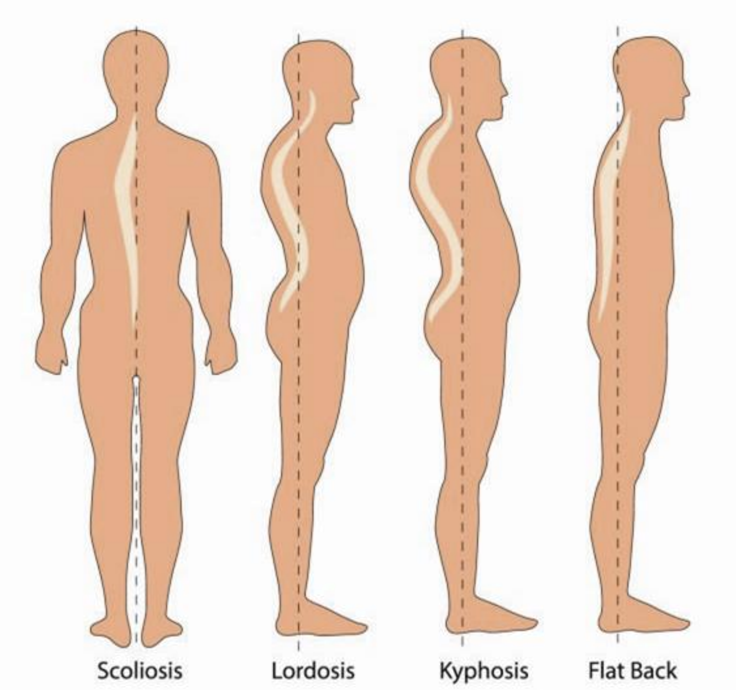
Vertebral Osteotomies



- **6** different **types** of surgeries
- The **choice** depends on the **entity** of the **deformity** [3]

[1] KIM, Hong Jin, et al. (2020)
[3] KOSE, Kamil Cagri, et al. (2017)

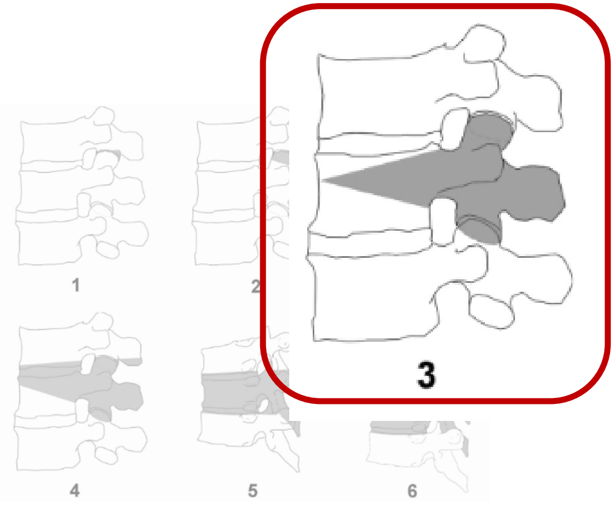
Clinical Problem



"**Spinal deformity** is **defined** as the spinal curvature or alignment that deviates from the normal limits" [1]

Spinal Surgeries

Vertebral Osteotomies



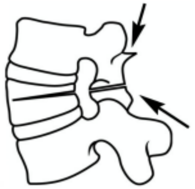
- **Pedicle Subtraction Osteotomy:**
  - ✓ Significant **angular correction** up to **30 - 40°** in the sagittal plane.
  - ✓ Effective for **rigid deformities**.
  - X More **invasive** and **technical** demanding.

Pedicle Subtraction Osteotomy (PSO)

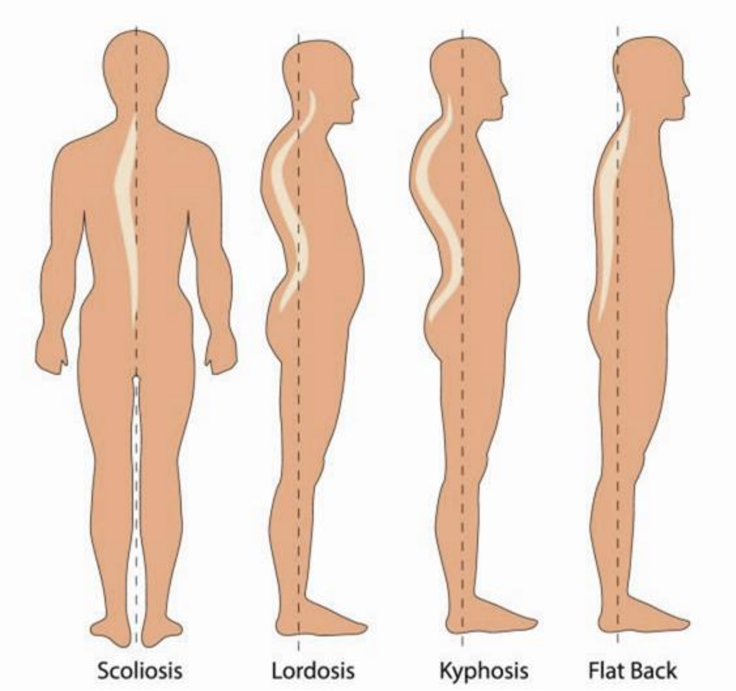
1. Subtraction of the posterior elements

2. Decancellation of the vertebral body

3. Closure of the osteotomy



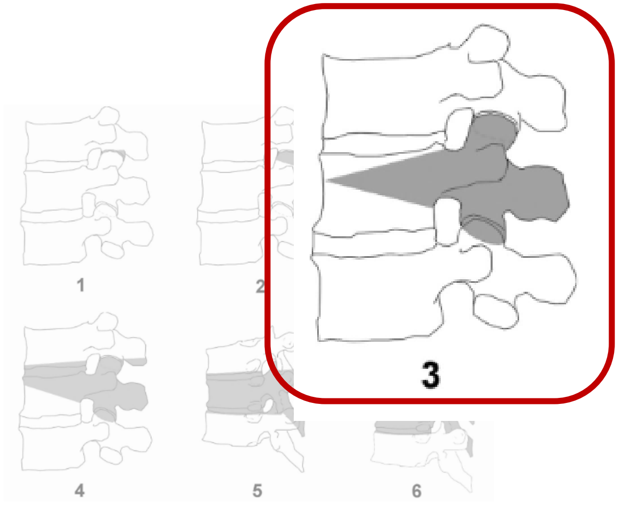
Clinical Problem



“Spinal deformity is **defined** as the spinal curvature or alignment that deviates from the normal limits” [1]

Spinal Surgeries

Vertebral Osteotomies



- **Pedicle Subtraction Osteotomy:**
  - ✓ Significant **angular correction** up to **30 - 40°** in the sagittal plane.
  - ✓ Effective for **rigid deformities**.
  - X More **invasive** and **technical** demanding.

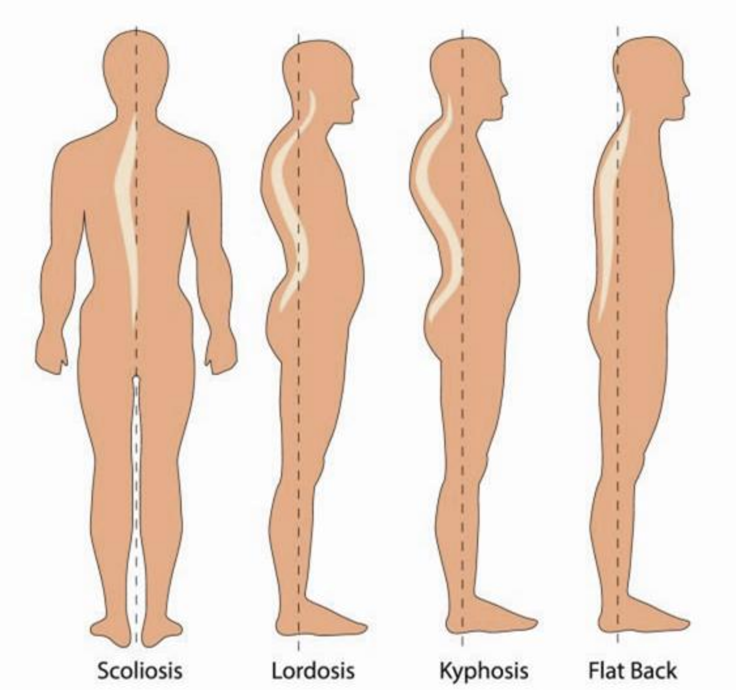
Pedicle Subtraction Osteotomy (PSO)

1 Subtraction of the posterior elements

2 Decancellation of the vertebral body

3 Closure of the osteotomy

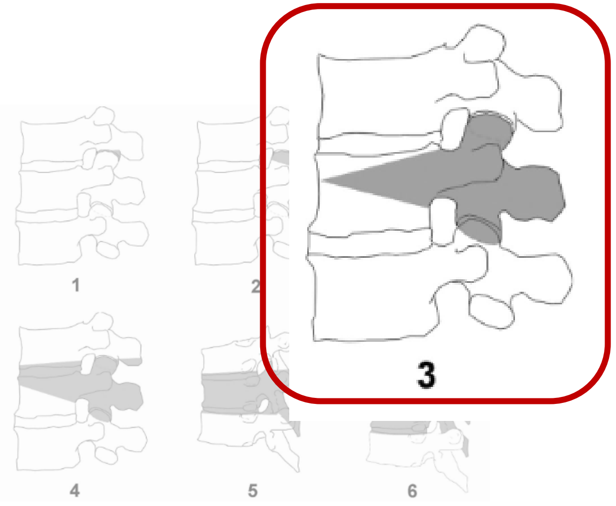
Clinical Problem



"**Spinal deformity** is **defined** as the spinal curvature or alignment that deviates from the normal limits" [1]

Spinal Surgeries

Vertebral Osteotomies



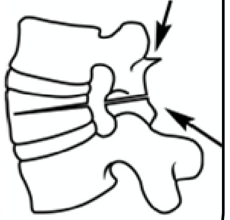
- **Pedicle Subtraction Osteotomy:**
  - ✓ Significant **angular correction** up to **30 - 40°** in the sagittal plane.
  - ✓ Effective for **rigid deformities**.
  - ✗ More **invasive** and **technical** demanding.

Pedicle Subtraction Osteotomy (PSO)

1. Subtraction of the posterior elements

2. Decancellation of the vertebral body

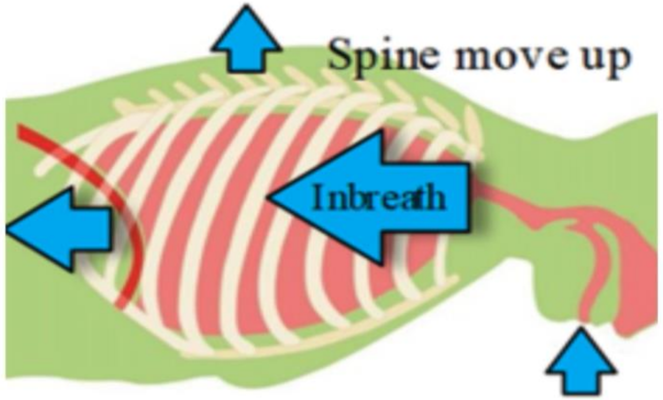
3. Closure of the osteotomy



Limitations of PSO procedure

Currently only **manually performed** with osteotomes and fluoroscopy

- ❌ **High** surgeon's **workload**
- ❌ High **radiation exposure**
- ❌ **Limited** surgical **precision**



Respiration induced vertical **vertebral displacement** [4]

- ❌ **Vertical displacement** around **2-4mm** [4]
- ❌ **Risk** of tissue **damage**
- ❌ **Compromise** overall surgical **accuracy**

Robotic systems in **spine surgery**

Commercially available

- **Pedicle Screw Fixation**

Rosa Spine robotic system [5]

© Zimmer Biomet

Experimental Level

- **Osteotomy [6]**

'Autonomous image-guided robotic system for Vertebral Osteotomy'

- ✓ **No fatigue**
- ✓ Increased **Precision**
- ✗ Only **Spinous Process** and **Lamina**

Respiratory Compensation **Robotic** systems in **spine surgery**

Commercially available

- **Passive compensation**

Mazor Robotic Renaissance [7]

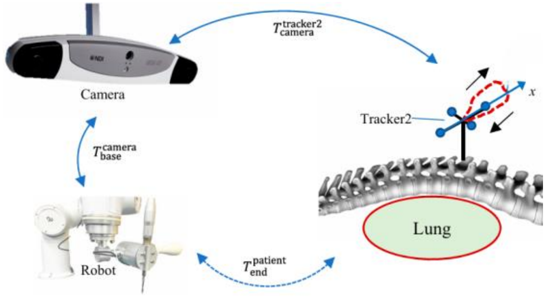
© Ortho Carolina

- ✓ **Rigidly** attached to the **vertebra**
- ✗ Bone **stiffness** requirements

Experimental Level

- **Active compensation**

'Respiratory motion prediction in spine surgery' [8]



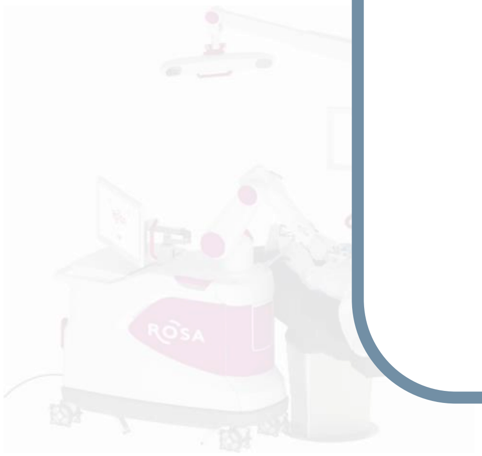
- ✓ **Real-time** compensation
- ✓ **Predictive** methods
- ✗ **No Robotic Control**
- ✗ **Pedicle Screw Fixation**

Robotic systems in **spine surgery**

Commercially available | Experimental Level

- **Pedicle Screw Fi**

Rosa Spine robotic sy



© Zimmer Biomet

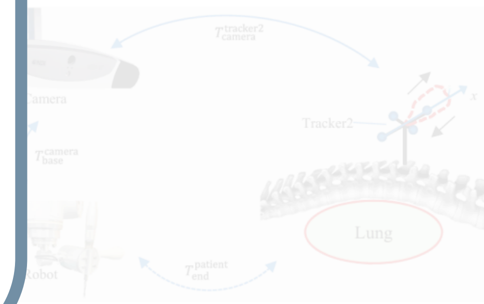
Increased **Precision**

Respiratory Compensation **Robotic** systems in **spine surgery**

Commercially available | Experimental Level

Active compensation

spiratory motion prediction in spine surgery' [8]



Rigidly attached to the **vertebra**

Bone stiffness requirements

Real-time compensation

Predictive methods

No Robotic Control

Pedicle Screw Fixation

Lack of Robotic Systems for Spinal Osteotomy procedures with active compensation of respiratory induced vertebral movements

[5] JIANG, Bowen, et al. (2019)
[6] PV Bhagvath, P Mercier, and AF Hall . (2023)
[7] LEE, Nathan J., et al. (2018)
[8] HAN, Zhe, et al. (2024)

Aim of the work

Clinical Goal

- **Avoid** risk **of tissue damage**
- **Improve** procedure **accuracy**
- **Reduce** surgeon's **workload**

Technical Goal

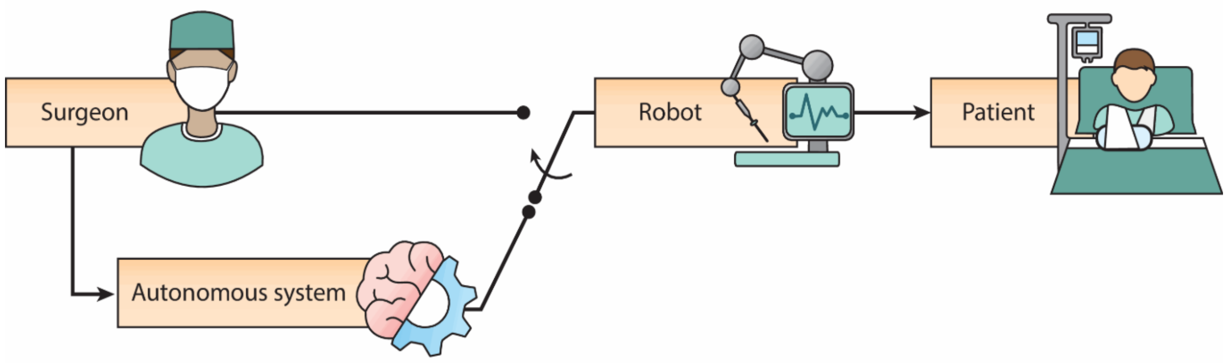
- **Following pre-defined cutting planes**
- **Sub-millimeter precision** during **drilling procedure**
- **Compensate** for **respiratory** induced **vertebral displacement**

Solution

Autonomous Robot Control Strategy

Clinical Goal

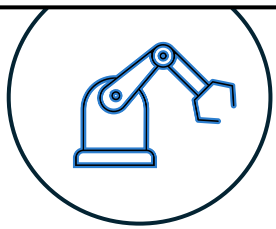
- **Avoid** risk **of tissue damage**
- **Improve** procedure **accuracy**
- **Reduce** surgeon's **workload**

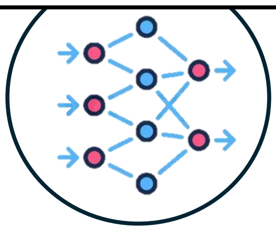


Technical Goal

- **Following pre-defined cutting planes**
- **Sub-millimeter precision** during **drilling procedure**
- **Compensate** for **respiratory** induced **vertebral displacement**

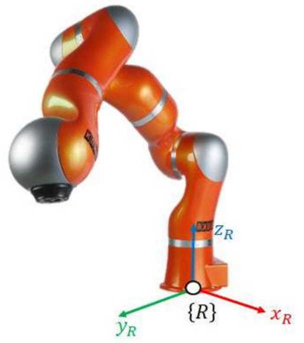
Hybrid Force-Position Control strategy ⇄ **Respiratory Motion Prediction Algorithm**





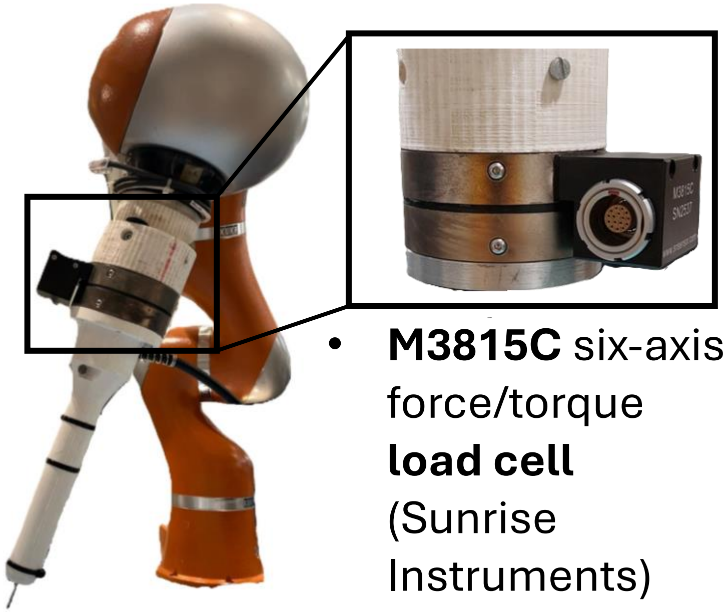
Materials

Robotic Manipulator



7 DoF (Degrees of Freedom) serial manipulator (**KUKA LwR 4+**)

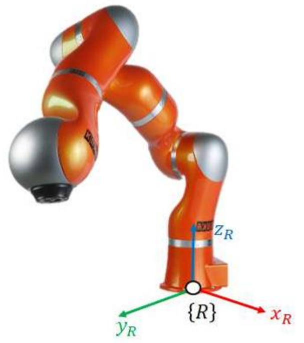
Load Cell & Drill



- **M3815C** six-axis force/torque **load cell** (Sunrise Instruments)

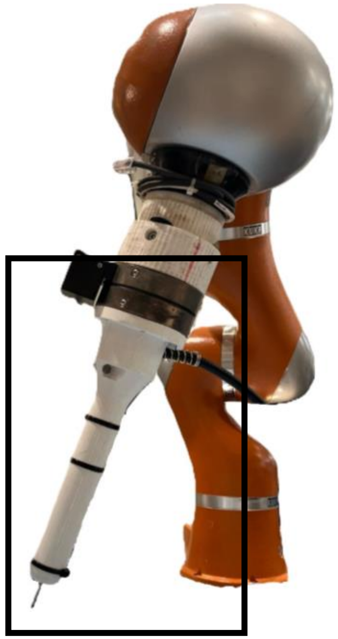
Materials

Robotic Manipulator



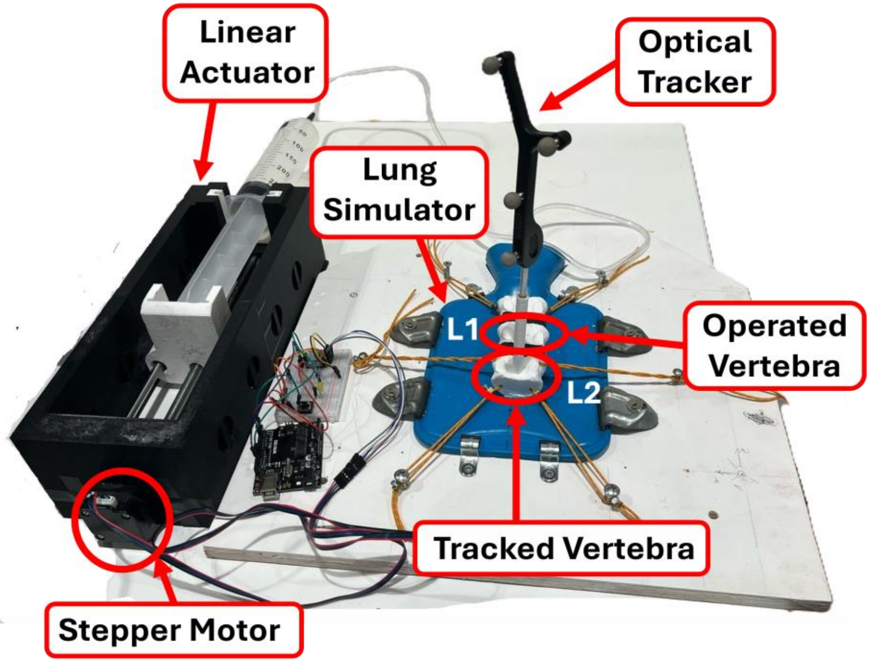
7 DoF (Degrees of Freedom) serial manipulator (**KUKA LwR 4+**)

Load Cell & Drill



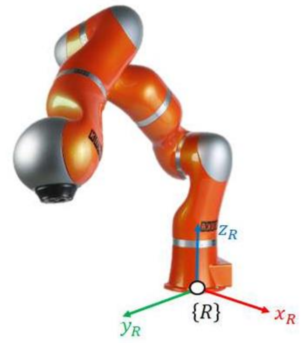
Drill:
- Motor with 5 velocities
- Power : 130 W
- Tip: Rotary Burr [$\emptyset$ 3 mm]

Respiratory Simulator



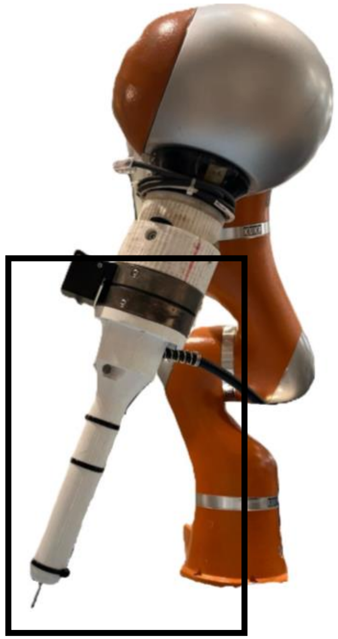
Materials

Robotic Manipulator



7 DoF (Degrees of Freedom) serial manipulator (**KUKA LwR 4+**)

Load Cell & Drill



Drill:
- Motor with 5 velocities
- Power : 130 W
- Tip: Rotary Burr [$\emptyset$ 3 mm]

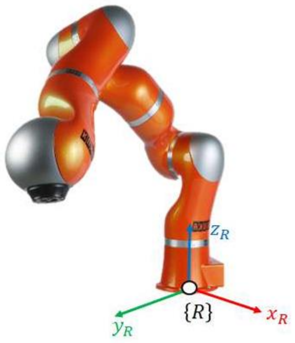
Respiratory Simulator

NDI Polaris Vicra
Optical Tracking System

Tracked Vertebra **(L2)**

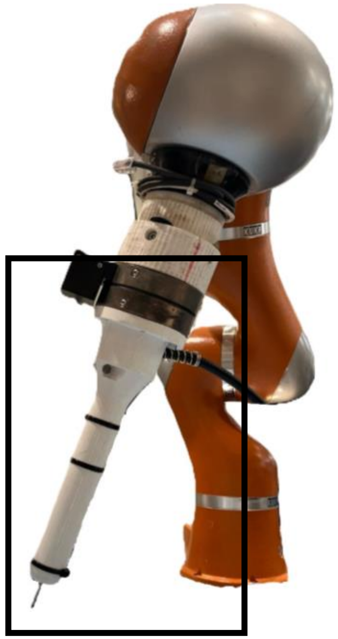
Materials

Robotic Manipulator



7 DoF (Degrees of Freedom) serial manipulator (**KUKA LwR 4+**)

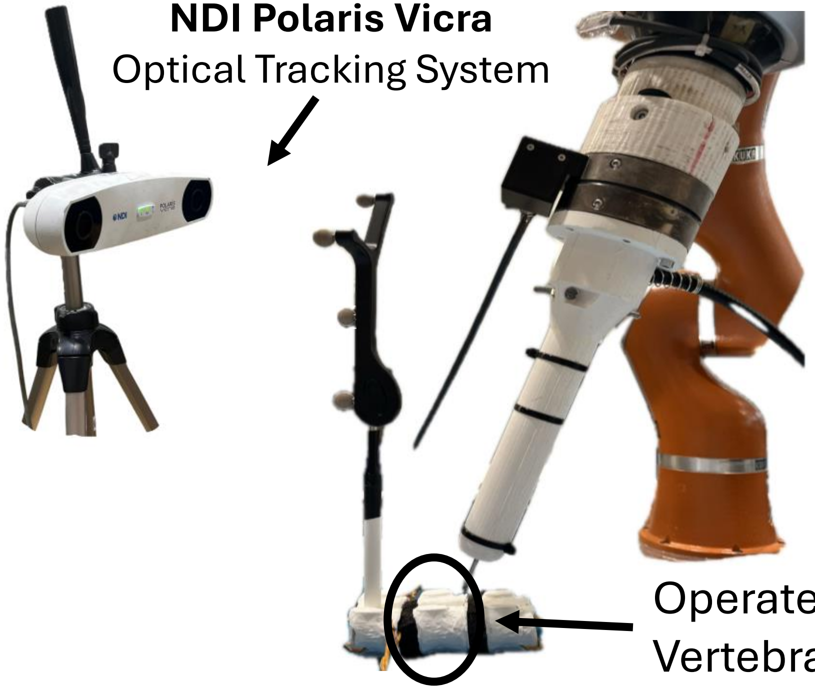
Load Cell & Drill



Drill:
- Motor with 5 velocities
- Power : 130 W
- Tip: Rotary Burr [$\emptyset\ 3\ mm$]

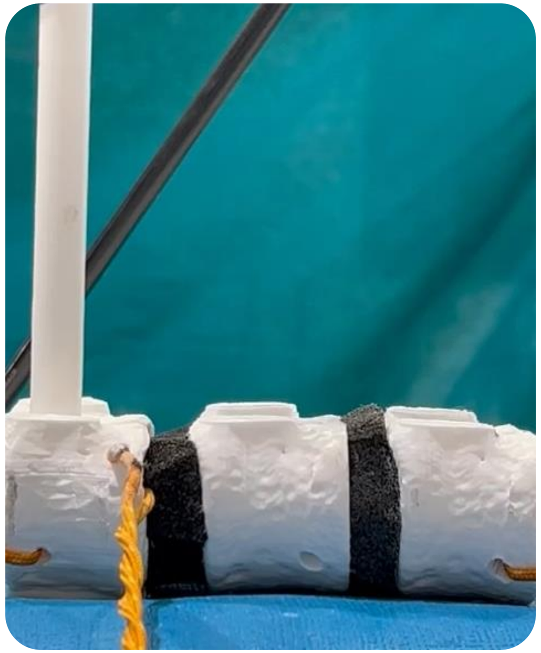
Respiratory Simulator

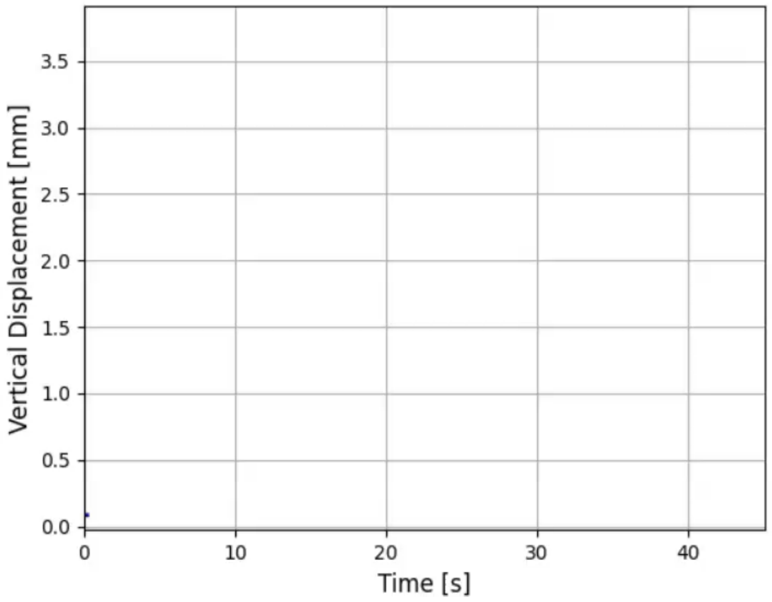
NDI Polaris Vicra
Optical Tracking System



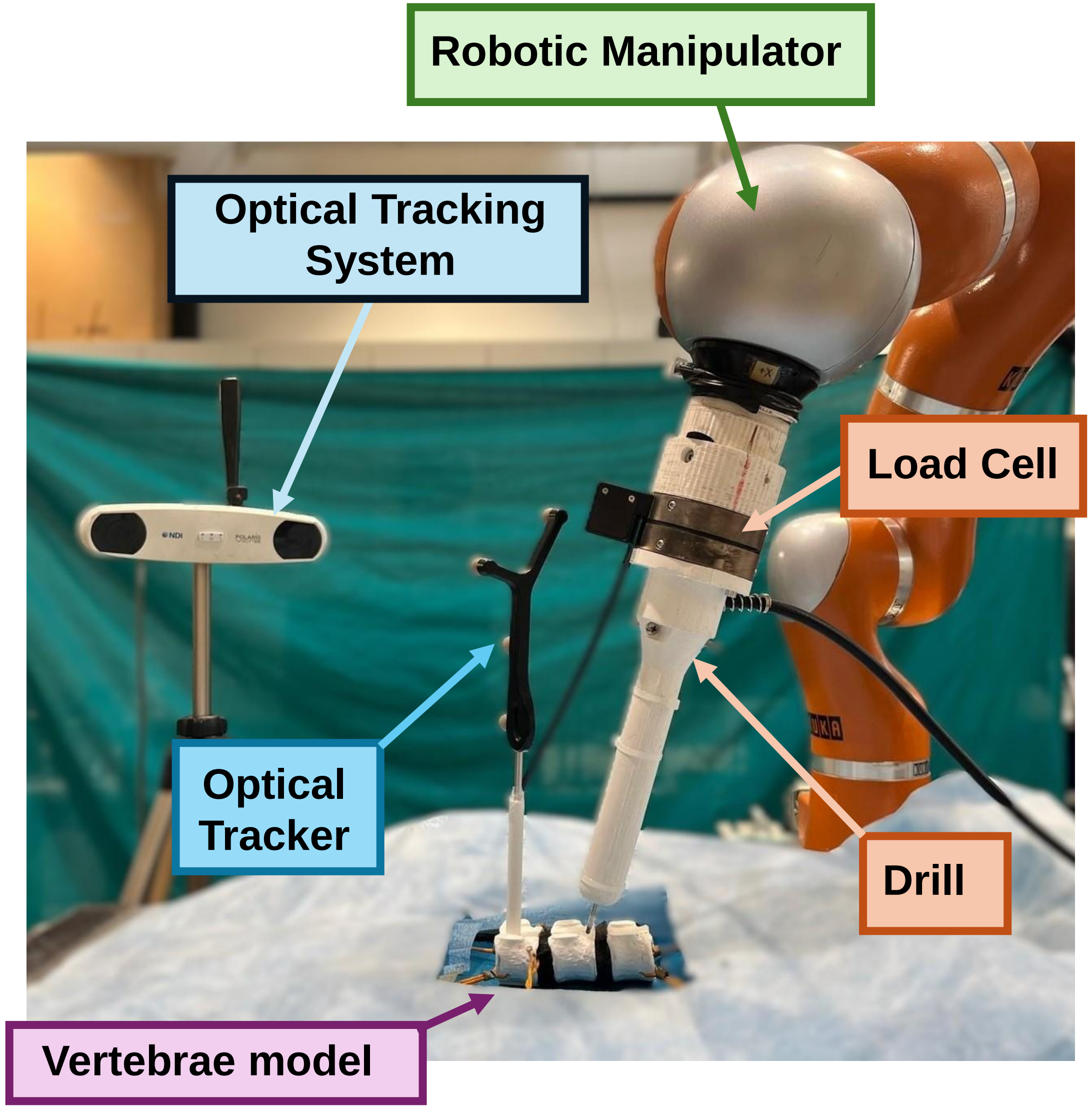
Operated Vertebra **(L1)**

Respiratory Simulator



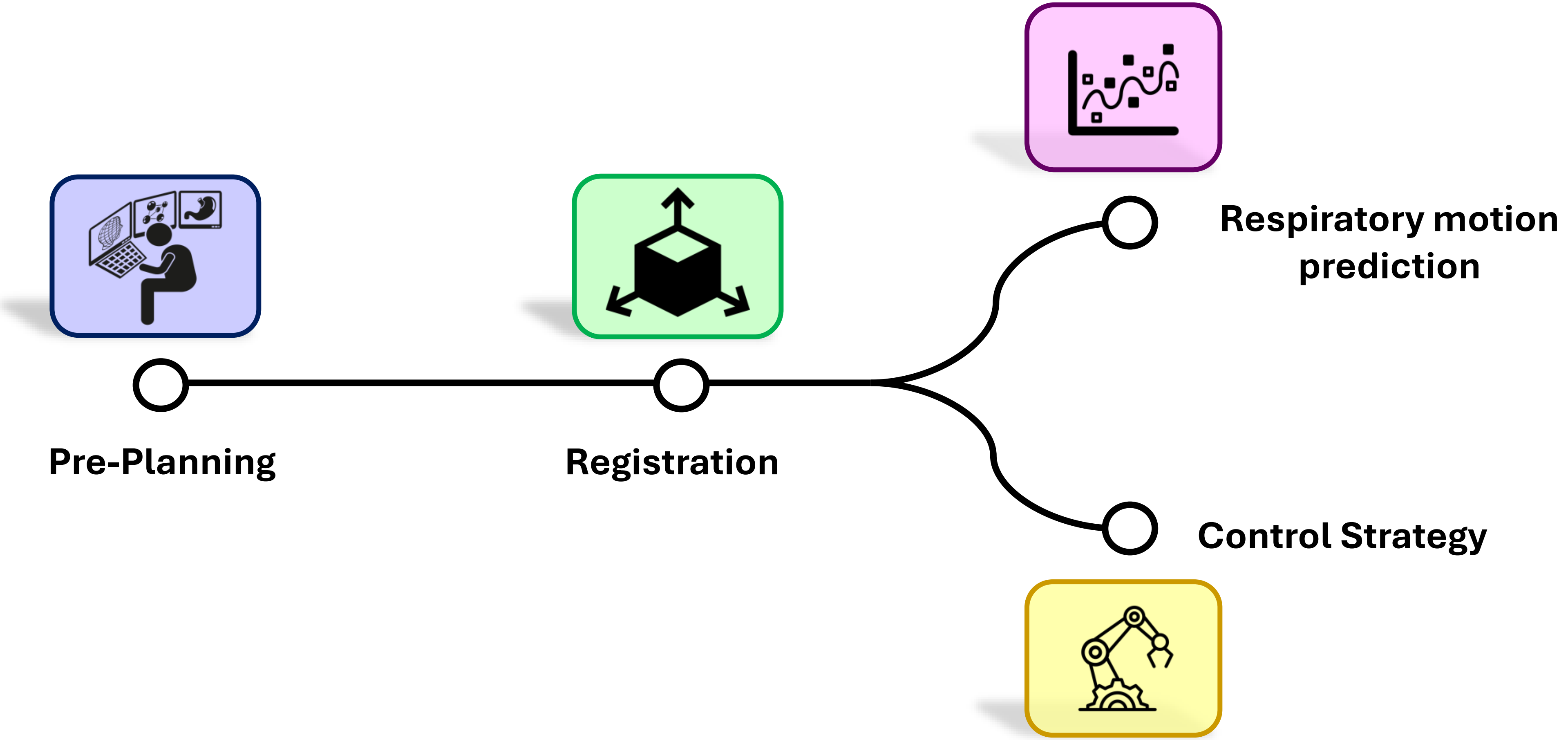


- Amplitude = 3.5 mm
- Frequency = 0.1 Hz [9]



[9] LIU, Yajun, et al. (2016)

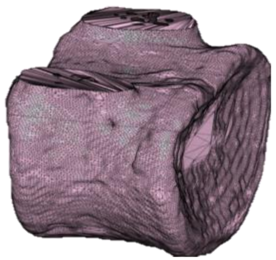
Methods

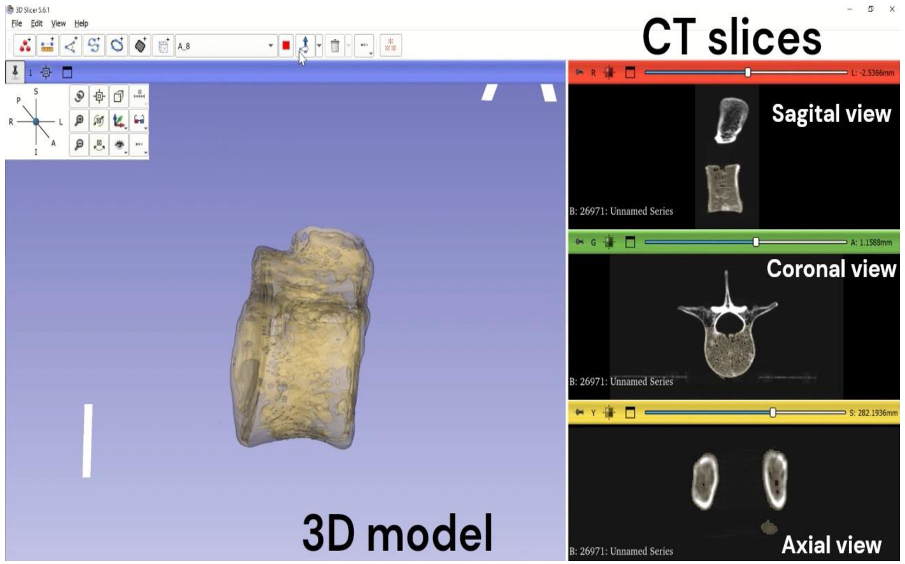

Respiratory motion prediction
Pre-Planning
Registration
Control Strategy

Pre-Planning

3D Slicer

Definition of the cutting planes and the relative vertex
(sagittal view)

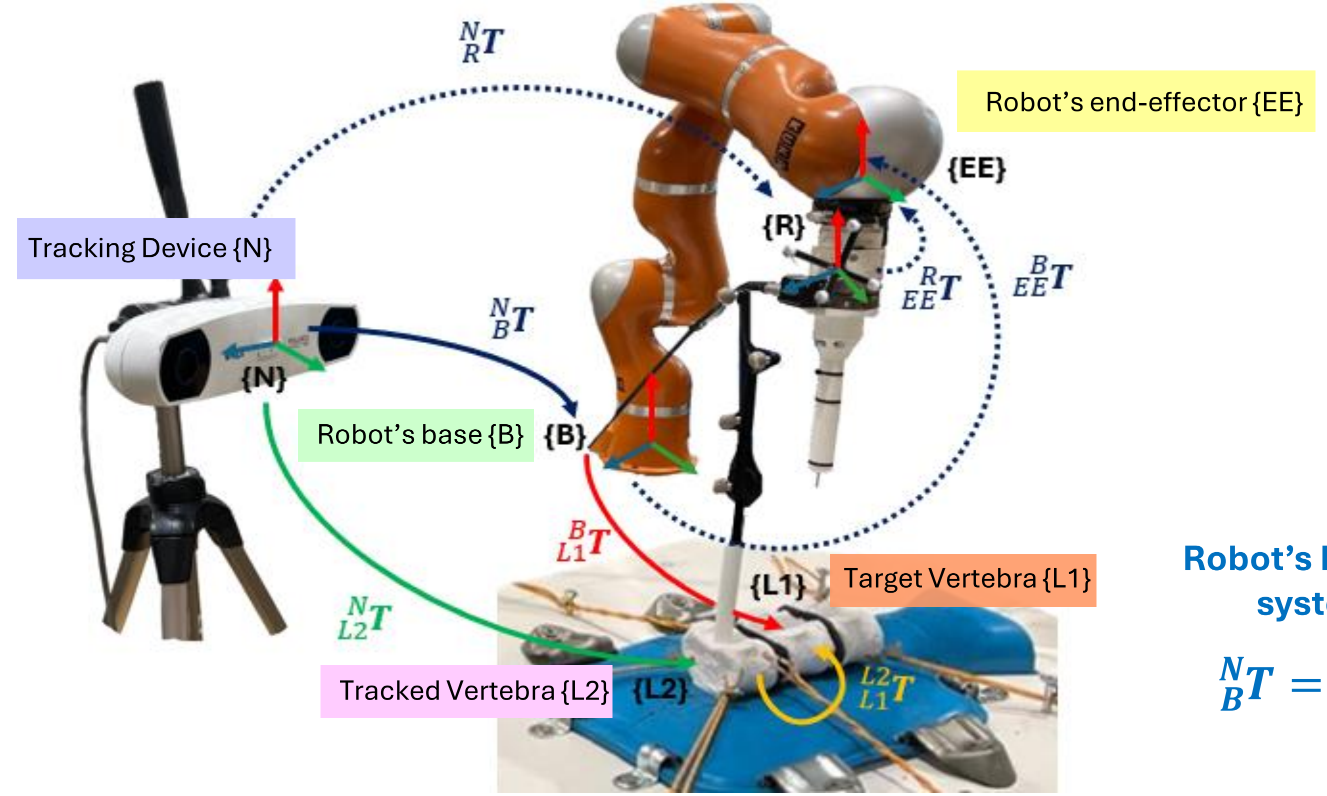




Osteotomy cutting planes

Vertex of the cutting planes

Registration



Target Vertebra {L1} coordinates in Robot's base reference frame {B}

$$ {}^{B}_{L1}T = \boxed{({}^{N}_{B}T)}^{-1} * \boxed{{}^{N}_{L2}T} * \boxed{{}^{L2}_{L1}T} $$

Robot's base {B} in **optical tracking system{N}** reference frame

$$ {}^{N}_{B}T = {}^{R}_{EE}T * {}^{N}_{R}T * ({}^{B}_{EE}T)^{-1} $$

Tracked Vertebra {L2} in **optical tracking system {N}** reference frame

Target Vertebra {L1} in **Tracked Vertebra {L2}**

Respiratory motion prediction

Different predictive algorithms' performances have been investigated.

Predictive Algorithms

1. Extended Kalman Filter (**EKF**). [10]
2. Deep Gated Recurrent Unit based network (**Deep GRU**). [11]
3. Deep Long Short Term Memory based network (**Deep LSTM**). [12]

Evaluation Metrics

Predictive approaches have been evaluated among the **same respiratory signals** retrieved during 14 drilling procedure.

Mean Absolute Error

- $\mathbf{MAE} = \frac{1}{N} \sum_{i=1}^{N} |y_i - \bar{y}_i| [mm]$

Root Mean Square Error

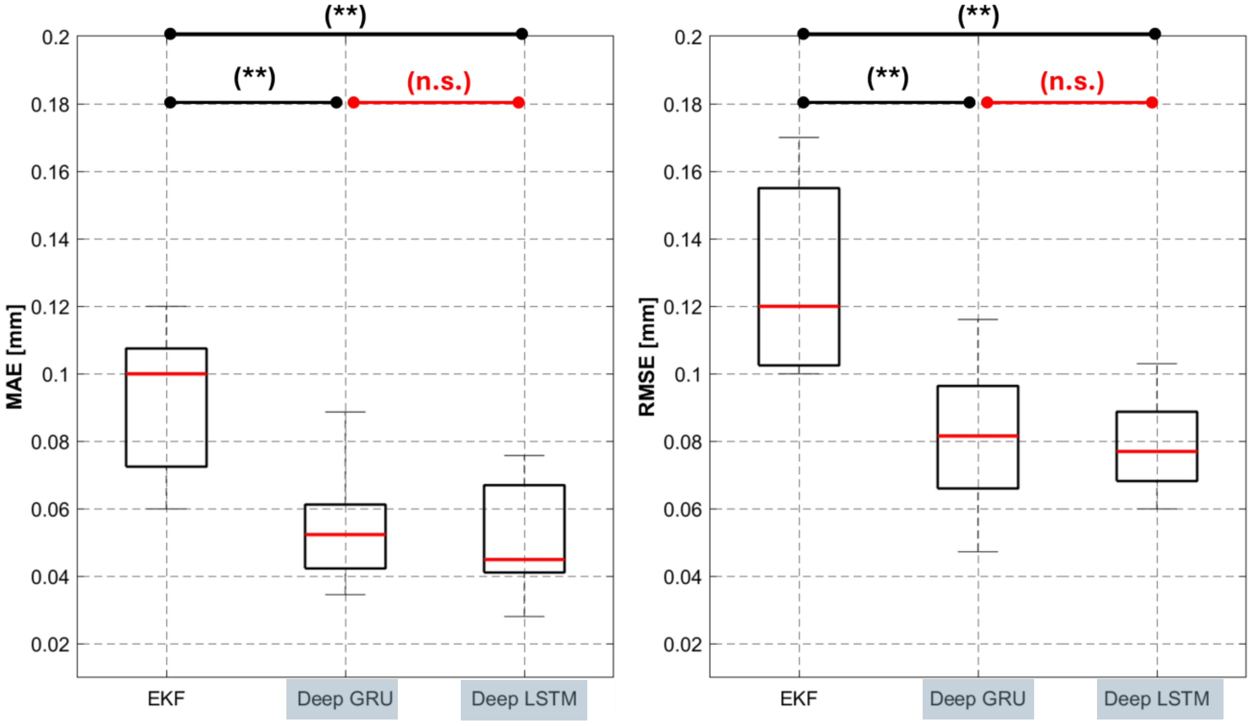
- $\mathbf{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (y_i - \bar{y}_i)^2}\ [mm]$

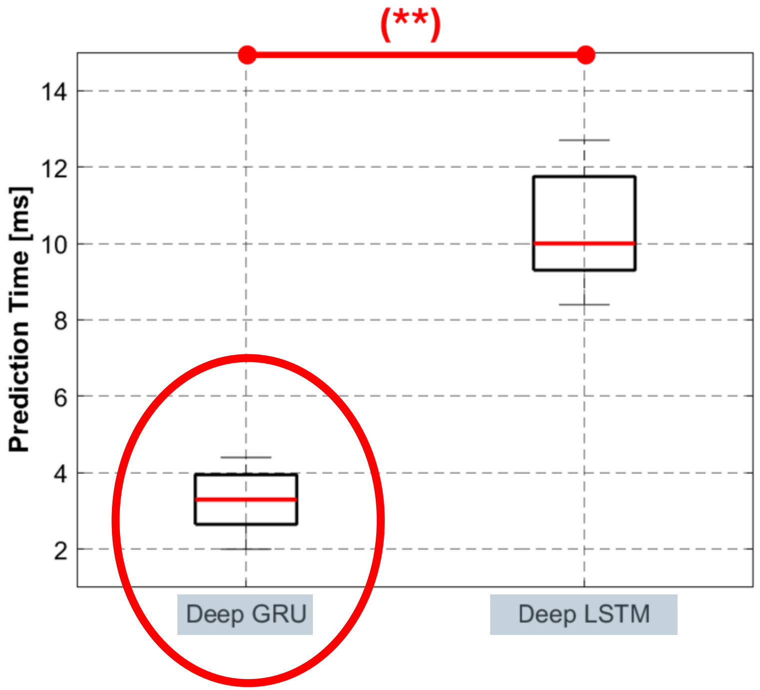
y_i is the current predicted value
$\bar{y}_i$ is the relative ground truth
N is the number of samples

[10] Lee, S. J., Motai, Y., & Murphy, M. (2011)
[11] YU, Shumei, et al. (2020)
[12] HAN, Zhe, et al. (2024)

Respiratory motion prediction

t-Student Test:
$**, p - value < 0.01$
$*, 0.01 < p - value < 0.05$
$n.s., p - value > 0.05$



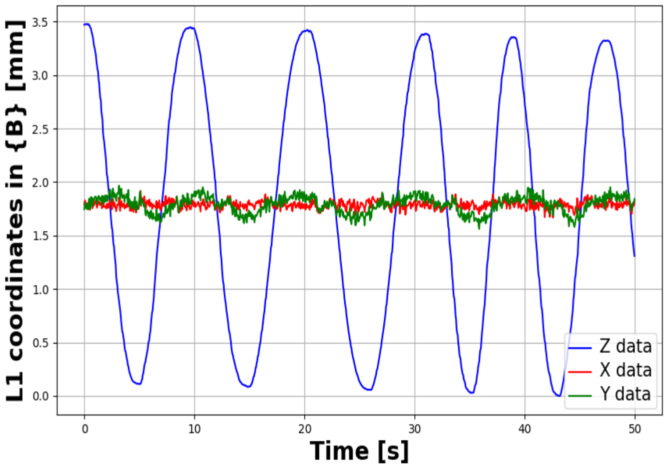


Respiratory motion prediction

Input

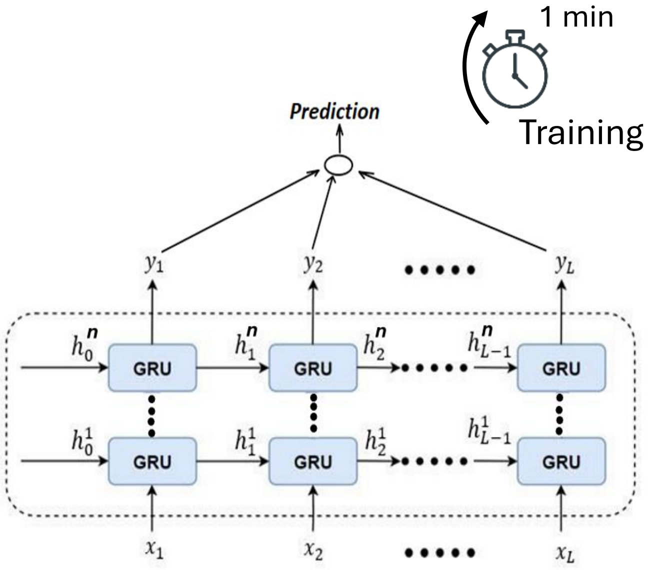
L1 z-coordinates in robot base reference frame **{B}**

- ✓ Adaptive Scaler applied



Predictive Algorithm

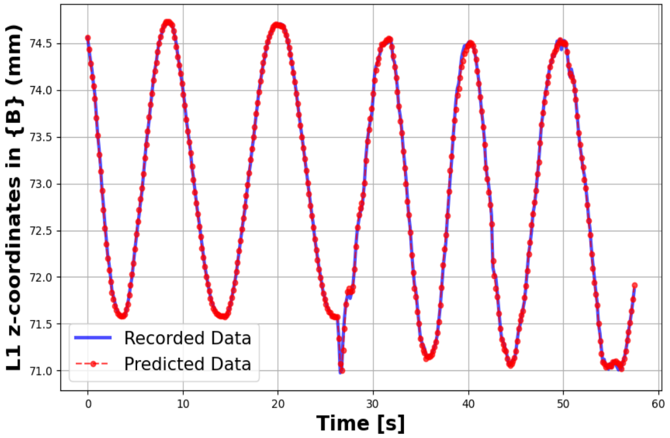
Deep Gated Recurrent Unit (GRU) based network



Output

Predicted L1 z-coordinates in robot reference frame **{B}** after a fixed **Time Delay** (150ms) [13]

- ✓ The **predicted point** is then sent to the **Robot control system.**

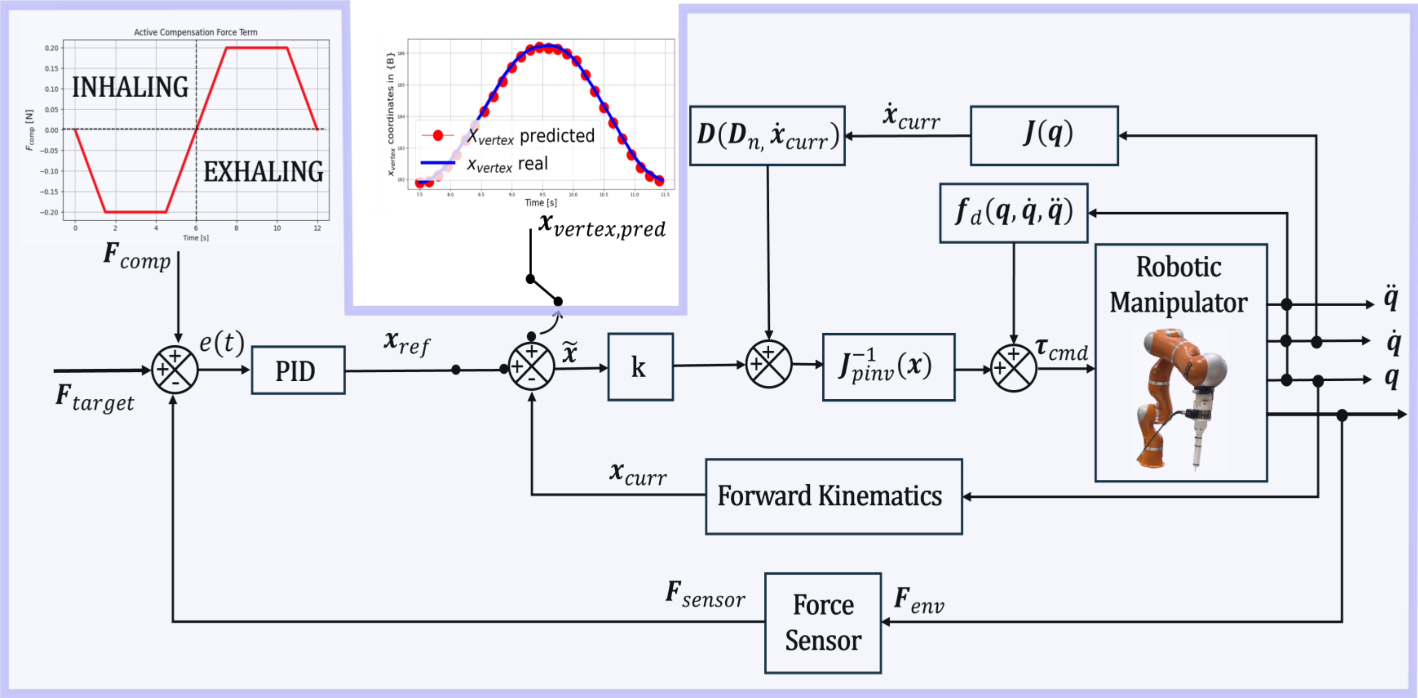


[13] YU, Shumei, et al. (2020)

ROS

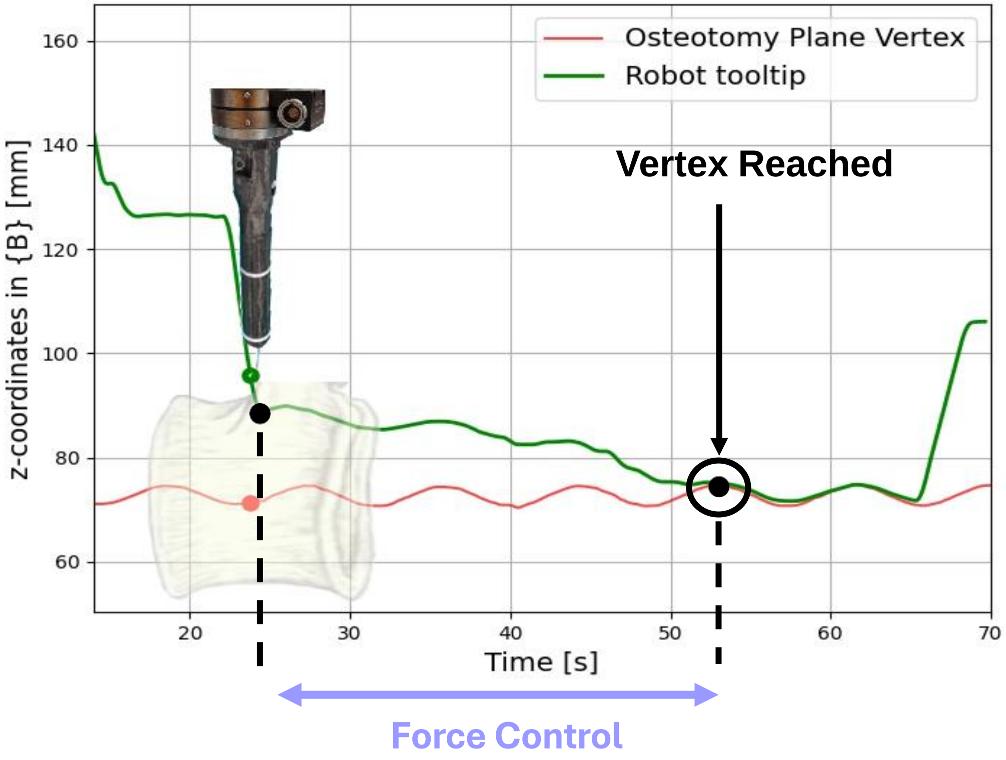
Control Strategy

Hybrid Force – Position control strategy



Force Control

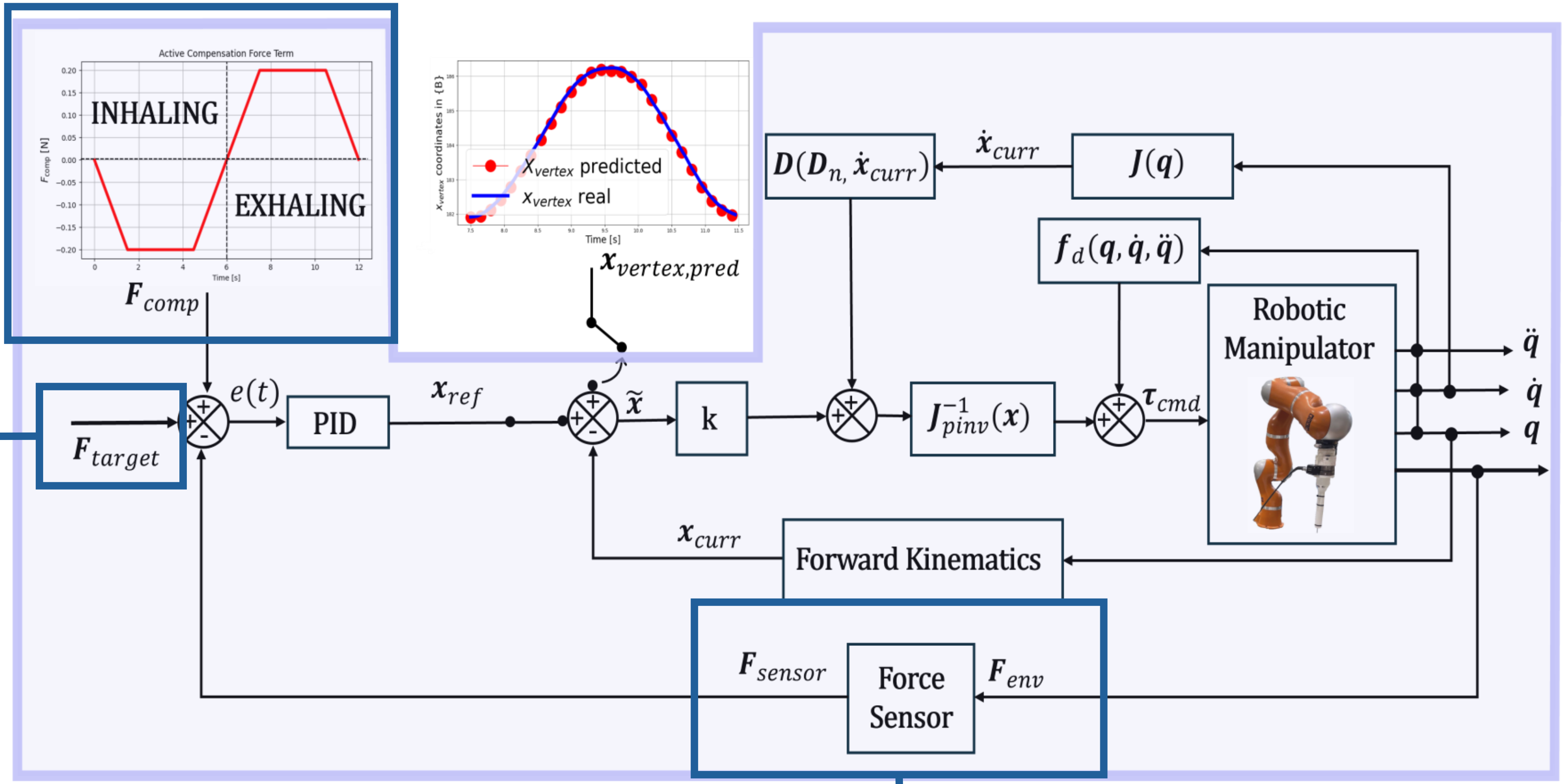
- ✓ The **control** is initially set to **force** to perform the cut.
- ✓ Maintain a **constant force** between the drill and the vertebra.



Force Control

Constant Drilling Force to be maintaned throughout the procedure set to **-2N**. [14]

✓ **Safety value** to avoid tissue damaging and too high contact forces.



Force signal retrieved from the load cell is **low-pass filtered**

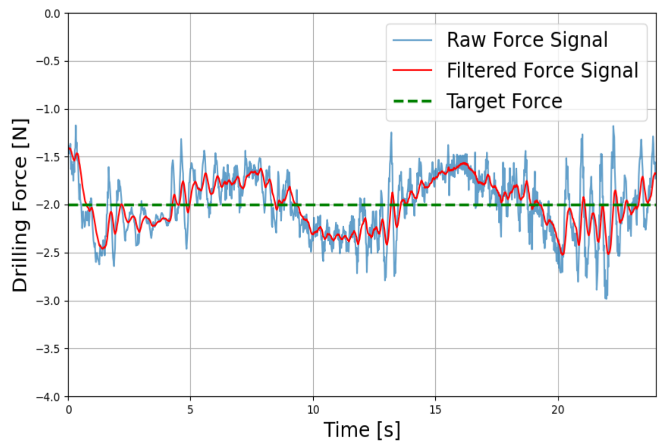
✓ Avoid undesired oscillations and potential tissue damage

$$F_{filt}(t) = \alpha * F_{sensor}(t) + (1-\alpha) * F_{filt}(t-1), \quad \alpha = 0{,}1$$

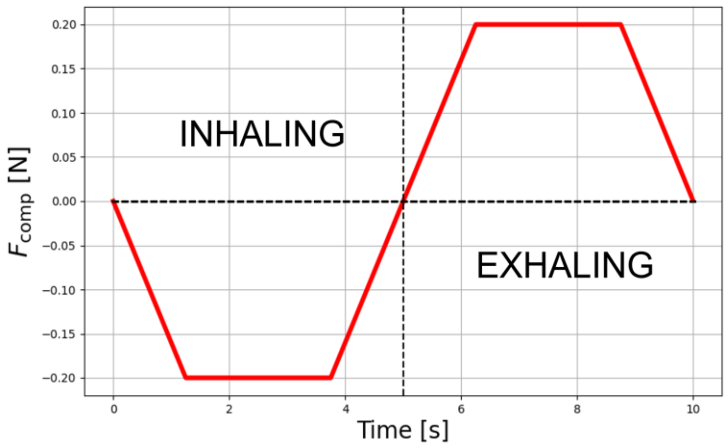
Active Compensation Force term

- ✓ **Avoid** drilling force's **periodic oscillation** around the force target value
- ✓ **Prevent instability**

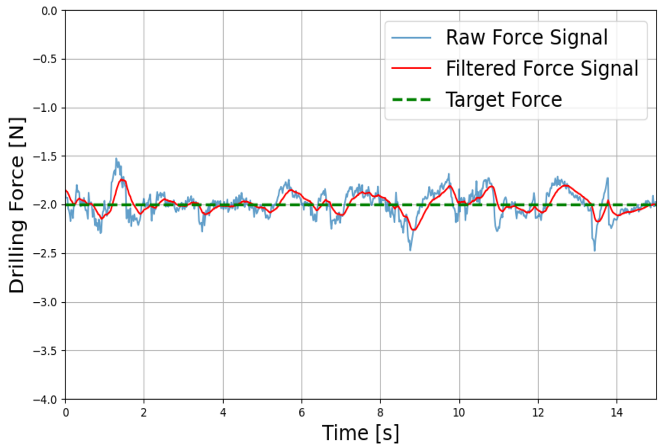
Force signal without compensation [15]



Active compensation Force Term

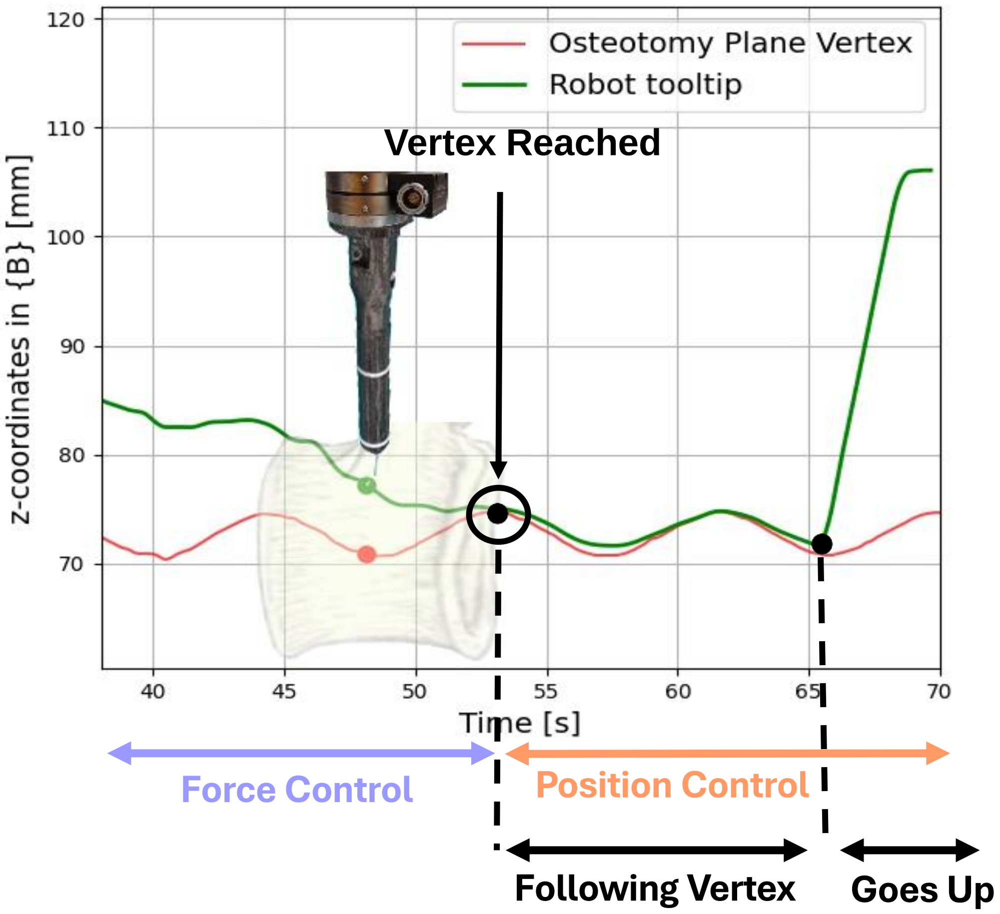


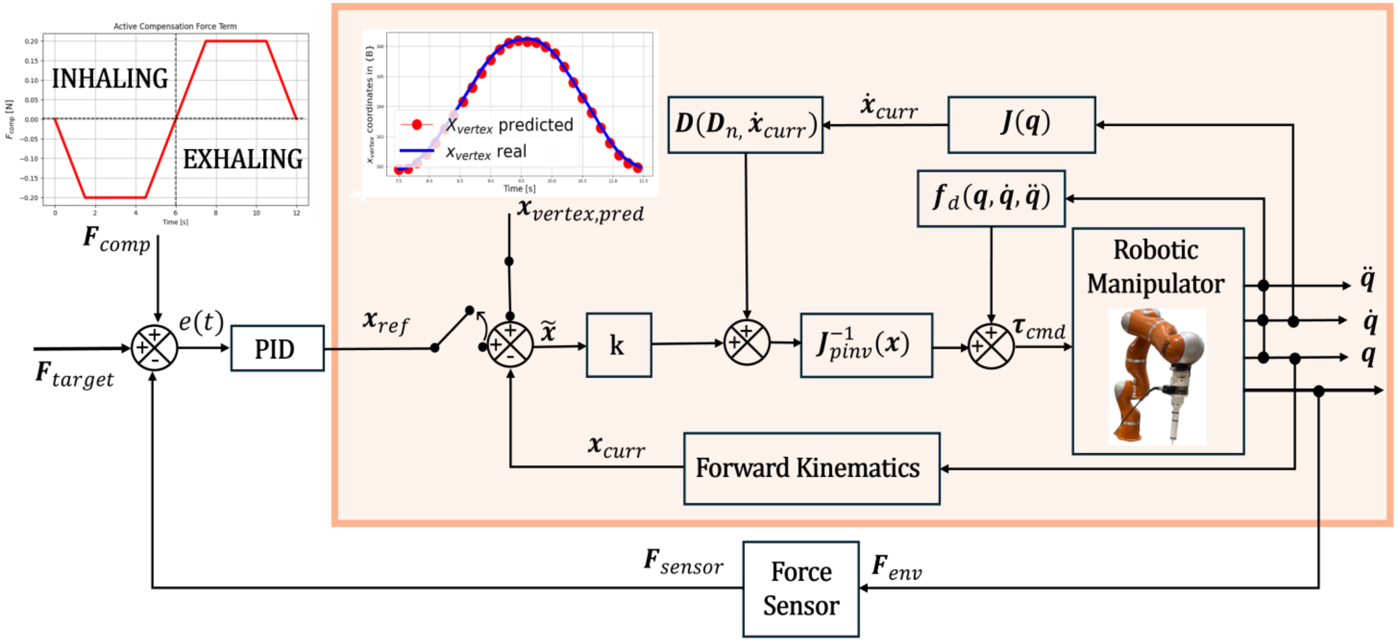
Force signal with compensation



[15] LI, Meng, et al. 2022

Position Control





The control switches from **Force** to **Position** as soon as the drill reaches the osteotomy planes' vertex:

1. The drill **reaches** the target vertex
2. The drill **follows** the target vertex
3. The drill **goes up**

✓ Ensure a **uniform** and **complete** cut

✓ **Prevent** the drill from going **beyond** the vertex point.

System Validation

Movement Prediction

- ✓ **Assess the accuracy of the predicted algorithm**

Force Control

- ✓ **Verify if the force remains constant at target value during the procedure**

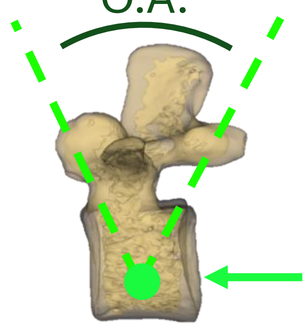
Position Control

- ✓ **Check if the osteotomy vertex is properly reached and followed**
- ✓ **Check if the cutting plane is followed**

Protocol

14 trials performed during the drilling of 3D PLA vertebra samples with the same **vertex position** to guarantee repeatability.

- ✓ **7** Drilling Trials with osteotomy angle (**O.A.**) = **30°**
- ✓ **7** Drilling Trials with osteotomy angle (**O.A.**) = **40°**



Movement Prediction

Evaluation Metrics

Mean Absolute Error (MAE)

- $\mathbf{MAE} = \frac{1}{N}\sum_{i=1}^{N}|y_i - \bar{y}_i| [mm]$

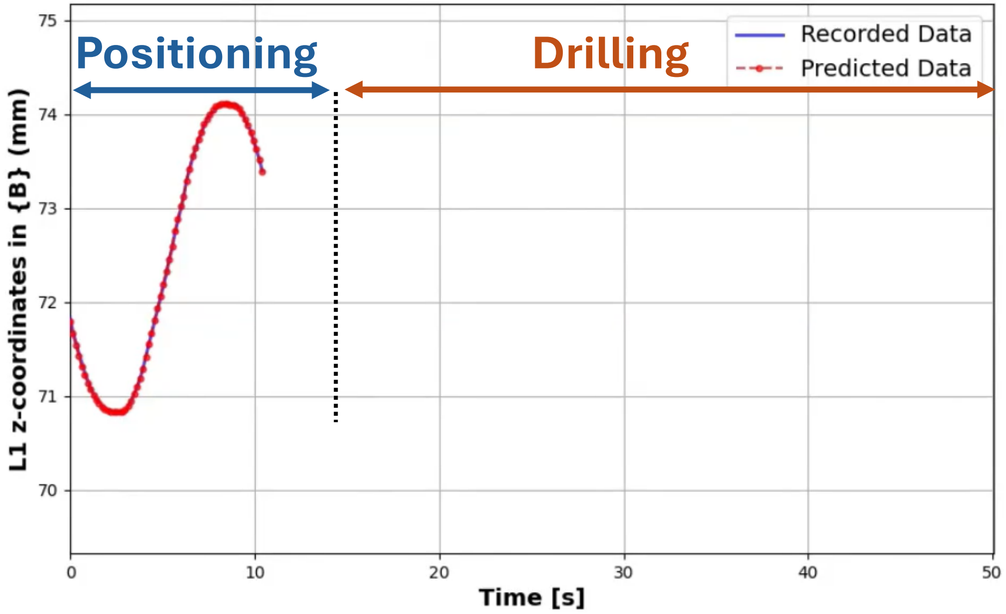
Root Mean Square Error (RMSE)

- $\mathbf{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(y_i - \bar{y}_i)^2}\ [mm]$

Maximum Error (ME)

- $\mathbf{ME} = \max_{i=1,..,n}|y_i - \bar{y}_i| [mm]$

y_i is the current predicted vertex value
$\bar{y}_i$ is the relative ground truth
N is the number of predicted points



	Positioning	Drilling
MAE [mm]	0,022 ± 0,02	0,047 ± 0,019
RMSE [mm]	0,027 ± 0,007	0,071 ± 0,021
ME [mm]	0,094 ± 0,016	0,21 ± 0,08

- ✓ **Small prediction errors** during both **positioning** and **drilling** phases.
- ✓ Metrics' values are in agreement with **literature** (errors within 0,3mm) [16], [17]

[16] YU, Shumei, et al. (2020)
[17] HAN, Zhe, et al. (2024)

Force Control

Evaluation Metrics

Mean Force Value (μ)

- $\mu = \frac{1}{N} \sum_{i=1}^{N} F_i \ [N]$

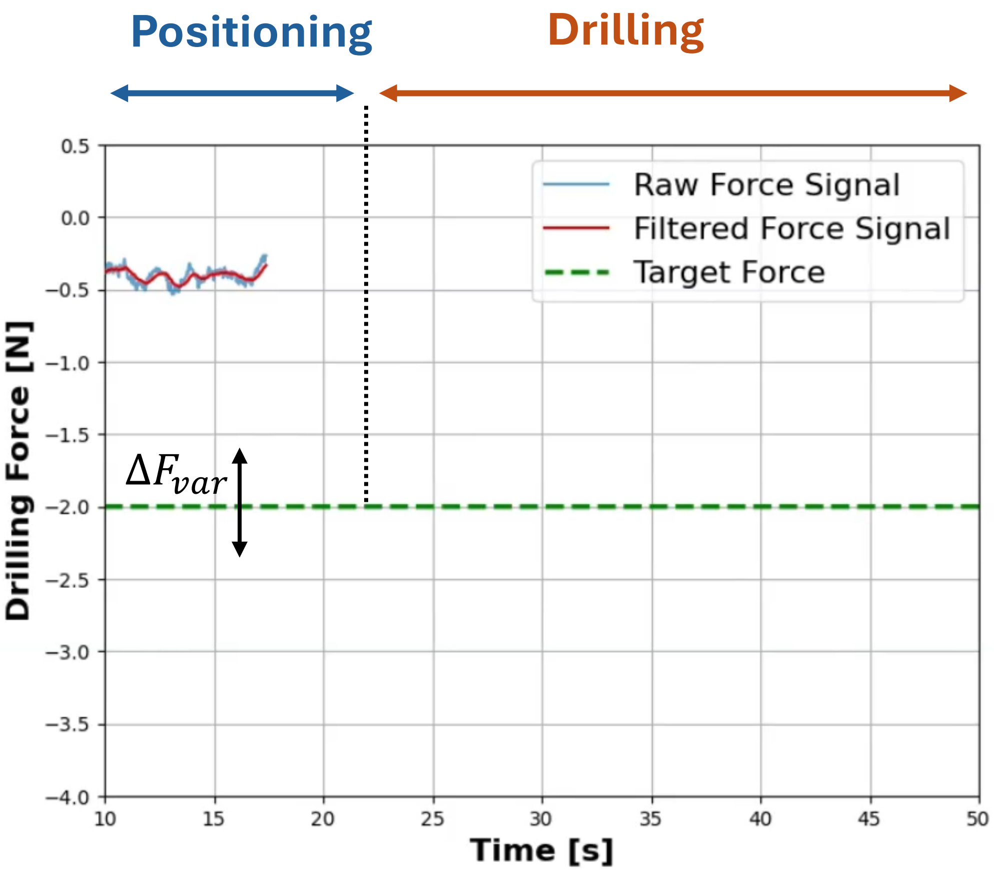
Standard Deviation (SD)

- $SD = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (F_i - \mu)^2} \ [N]$

Stability Factor [18]

- $\varphi = \frac{\sqrt{\sum_{i=1}^{N} (F_i - F_{target})}}{|\Delta F_{var}|} \ [\%]$

F_i : current Force value, F_{target} : target Force, N: number of samples, ΔF_{var} : force variation range



Force Control

Evaluation Metrics

Mean Force Value (μ)

- $\mu = \frac{1}{N} \sum_{i=1}^{N} F_i \; [N]$

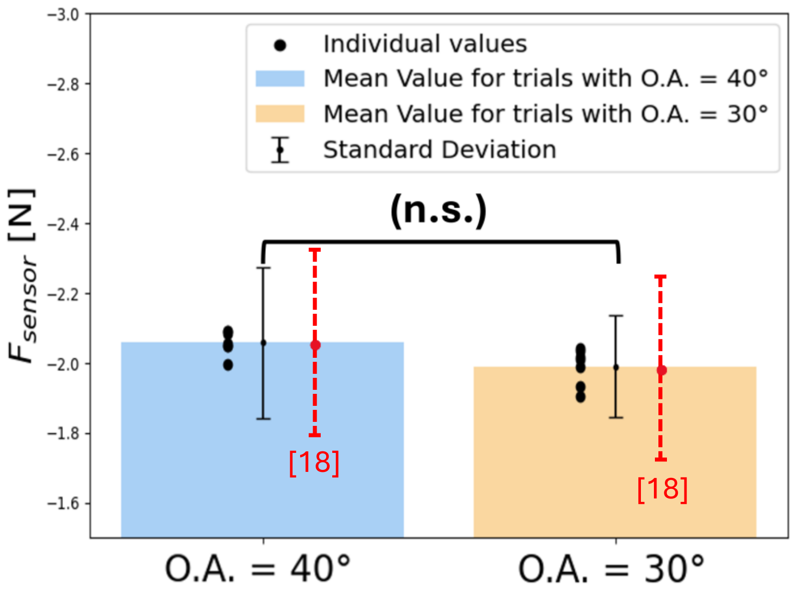
Standard Deviation (SD)

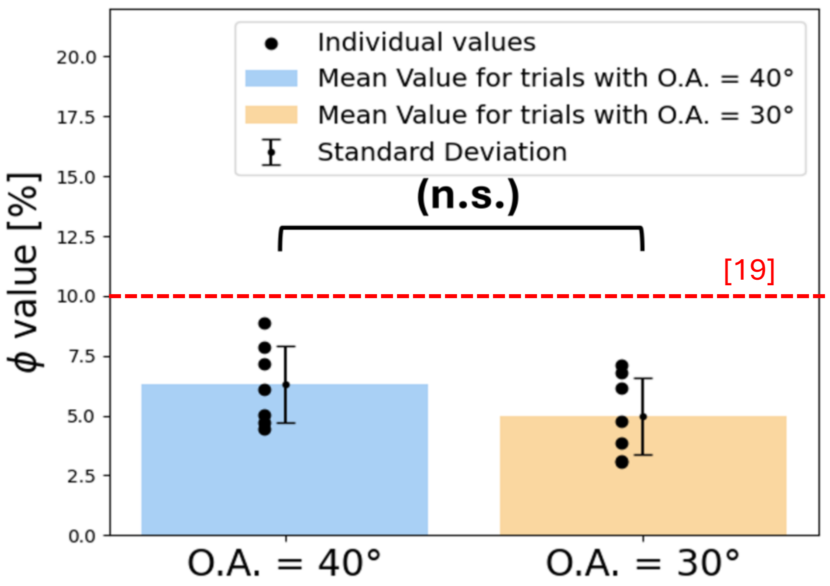
- $SD = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (F_i - \mu)^2} \; [N]$

Stability Factor [18]

- $\varphi = \frac{\sqrt{\sum_{i=1}^{N} (F_i - F_{target})}}{|\Delta F_{var}|} \; [\%]$

F_i : current Force value, F_{target} : target Force, N: number of samples, ΔF_{var} : force variation range





O.A.	40°	30°
μ, SD [N]	-2,053 ± 0,20	-1,98 ± 0,18
φ [%]	6,4 ± 1,58 %	4,98 ± 1,32 %

[18] LI, Meng, et al. (2022)
[19] Xia, G., Jiang, Z., & Dai, Y. (2024)

Force Control

Evaluation Metrics

Mean Force Value (μ

- $\mu = \frac{1}{N}\sum_{i=1}^{N} F_i$ [N

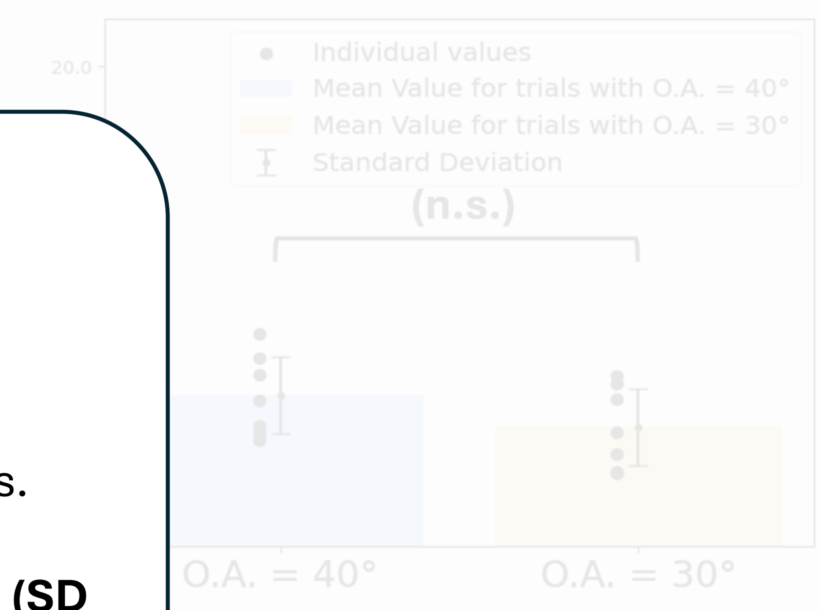
Standard Deviation (S

- $SD = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(F_i - \mu$

Stability Factor [18

- $\varphi = \frac{\sqrt{\sum_{i=1}^{N}(F_i - F_{target}}}{|\Delta F_{var}|}$

$\mathbf{F_i}$: current Force value, $\mathbf{F_{target}}$: target Force, N: number of samples, $\Delta \mathbf{F_{var}}$: force variation range



- ✓ Good **robustness** and **stability** during **drilling.**
- ✓ **Invariant** to different **osteotomy angles** entities.
- ✓ Metrics' values are in agreement with **literature (SD** within **0,2N** and **ϕ values** within **10%).** [20], [21]

		30°
μ, SD [N]	-2,033 ± 0,20	-1,98 ± 0,18
Φ [%]	6,4 ± 1,58 %	4,98 ± 1,32 %

[20] LI, Meng, et al. (2022)
[21] Xia, G., Jiang, Z., & Dai, Y. (2024)

Position Control

Evaluation Metrics

Trajectory Error

$$\mathbf{TJE} = \left\| P_{tool} - P_{proj} \right\| \ [mm]$$

Static Target Error

$$\mathbf{TE_{static}} = \left\| P_{tool} - P_{vert} \right\| \ [mm]$$

Dynamic Target Error

$$\mathbf{TE_{dynamic}} = \left\| P_{tool} - P_{vert} \right\| \ [mm]$$

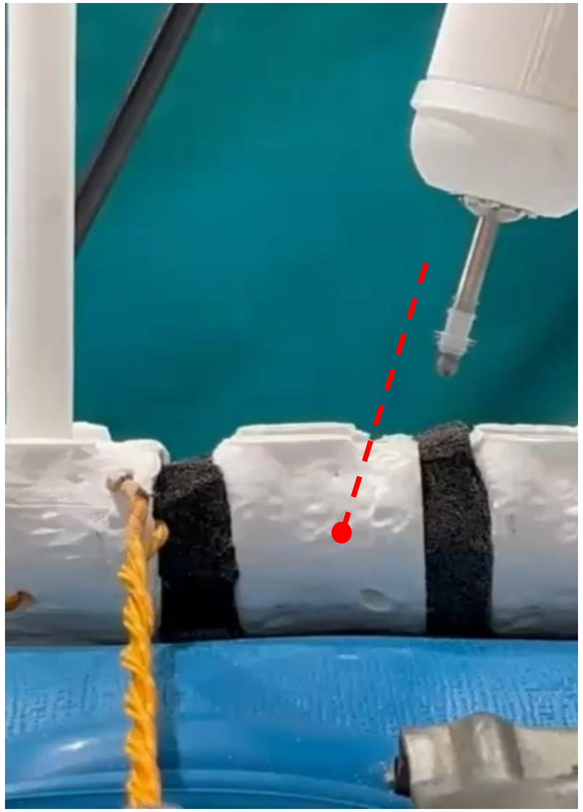
Vertex Crossing Count

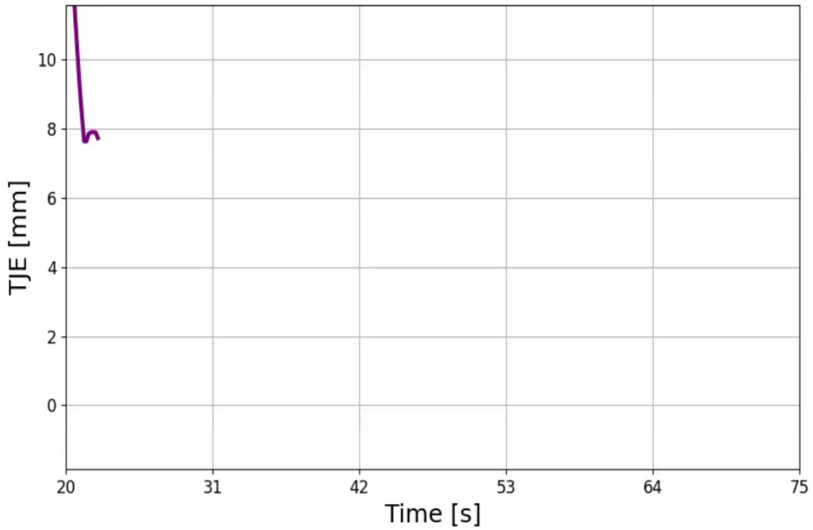
VCC = n° of Vertex Crossings

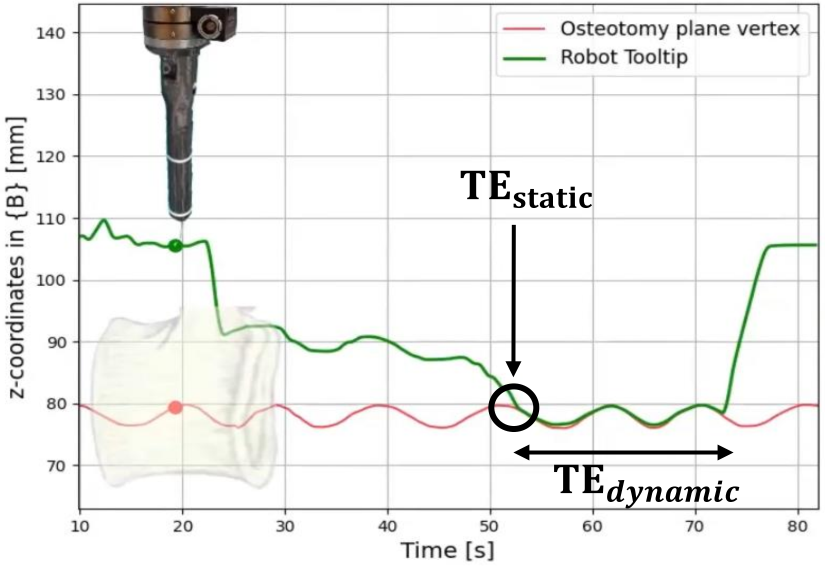
$\mathbf{P_{tool}}$: robot's tooltip position

$\mathbf{P_{proj}}$: orthogonal projection of P_{tool} on the osteotomy planes

$\mathbf{P_{vert}}$: osteotomy planes' vertex







Position Control

Evaluation Metrics

Trajectory Error

$$\mathbf{TJE} = \|P_{tool} - P_{proj}\| \ [mm]$$

Static Target Error

$$\mathbf{TE_{static}} = \|P_{tool} - P_{vert}\| \ [mm]$$

Dynamic Target Error

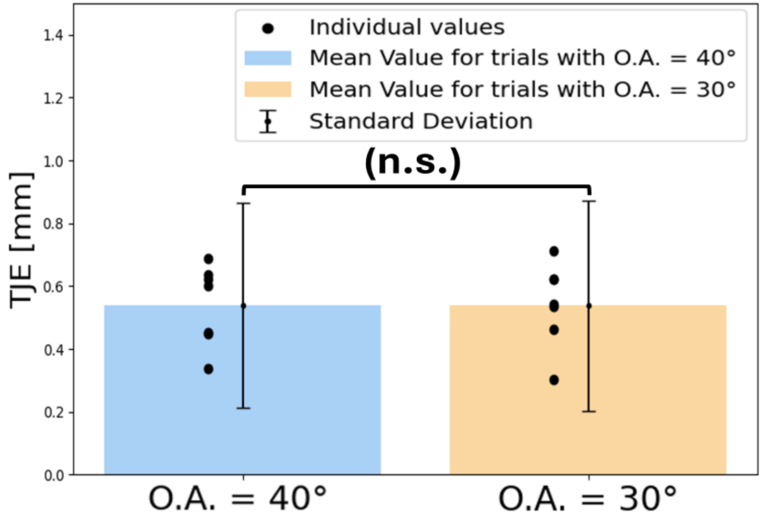
$$\mathbf{TE_{dynamic}} = \|P_{tool} - P_{vert}\| \ [mm]$$

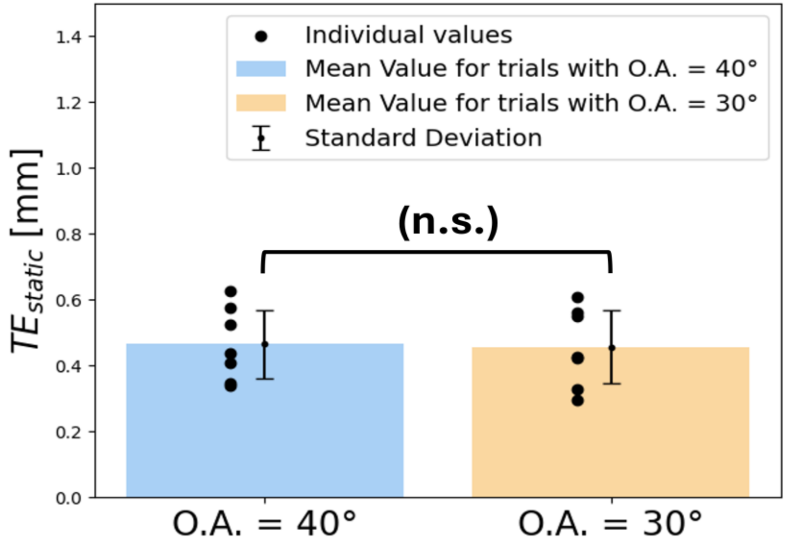
Vertex Crossing Count

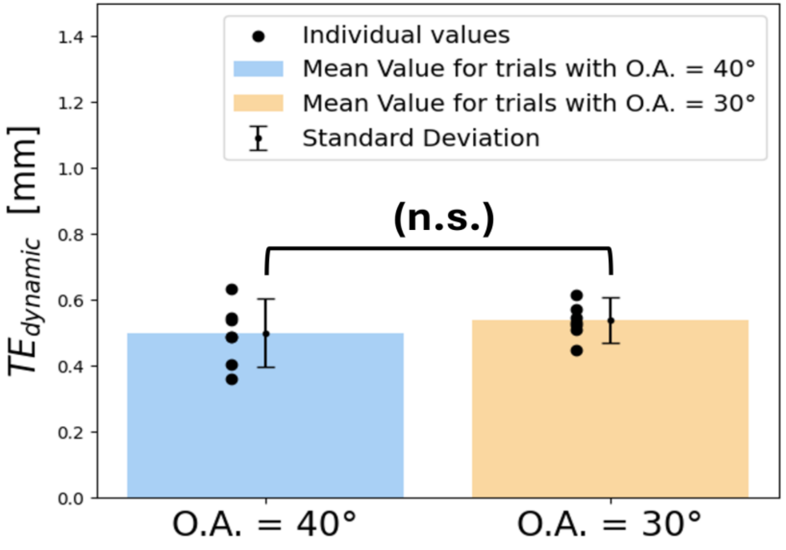
VCC = n° of Vertex Crossings

$\mathbf{P_{tool}}$: robot's tooltip position
$\mathbf{P_{proj}}$: orthogonal projection of $\mathrm{P_{tool}}$ on the osteotomy planes
$\mathbf{P_{vert}}$: osteotomy planes' vertex

O.A.	40°	30°
TJE [mm]	0,55 ± 0,31	0,54 ± 0,30
$\mathbf{TE_{static}}$ [mm]	0,45 ± 0,037	0,467± 0,02
$\mathbf{TE_{dynamic}}$ [mm]	0,55 ± 0,047	0,524 ± 0,043
VCC	0	0







Position Control

Evaluation Metrics

Trajectory Error

Static Target Error

Dynamic Target Erro

Vertex Crossing Cou

P_{tool}: robot's tooltip position
P_{proj}: orthogonal projection of P_{tool} on the osteotomy planes
P_{vert}: osteotomy planes' vertex

- ✓ System reaches and follows the **target** with **high precision**.
- ✓ Properly **follows** the pre-planned **osteotomy planes**.
- ✓ **Invariant** to different **osteotomy angles** entities.
- ✓ **Smaller errors** with respect to **freehand procedure** (5mm). [22]
- ✓ Values **within** the **safe margin** for **surgical procedures** (1-2mm). [23]

[22] ENGELHARDT, Martin, et al. (2004)
[23] FAN, Luping, et al. (2016)

ACHIEVEMENTS

An **autonomous hybrid** Force – Position robotic control coupled with **active respiratory** motion **compensation** algorithm has been developed for **Vertebral Osteotomy** surgical procedure

Clinical perspective:

- ✓ Less risk of tissue damage.
- ✓ Improved procedure accuracy.
- ✓ Reduced surgeon’s workload.

Technical perspective:

- ✓ Proper compensation of the respiratory induced vertebral displacement.
- ✓ Sub-millimeter precision.
- ✓ Invariant to different osteotomy angles entities.

Work Limitations

- More **realistic set-up**
- PLA vertebrae models not accounting for **internal stratification**
- **Fixed Target force** during drilling procedure
- Fixed **respiratory patterns**

Future Development

- Accounting for **intra-vertebral movements**
- Experiments with **real vertebra model**
- **Adaptive Force** algorithm to vertebra stratification
- Accounting for **variable respiratory-patterns**

Thank you for your attention!